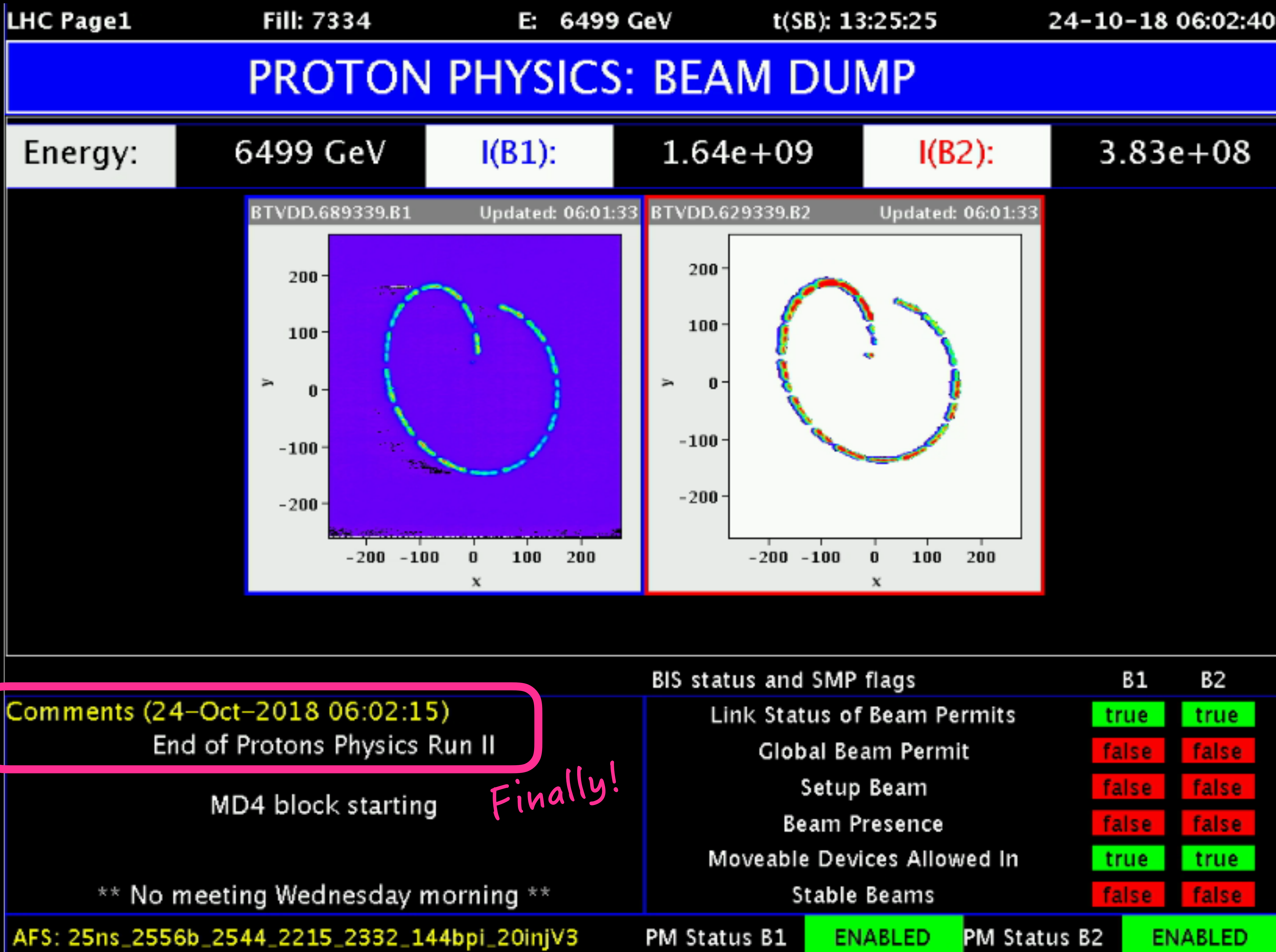
NCTS Annual Theory Meeting, Dec 18th, 2018

RECENT HIGHLIGHTS FROM THE LHC EXPERIMENTS

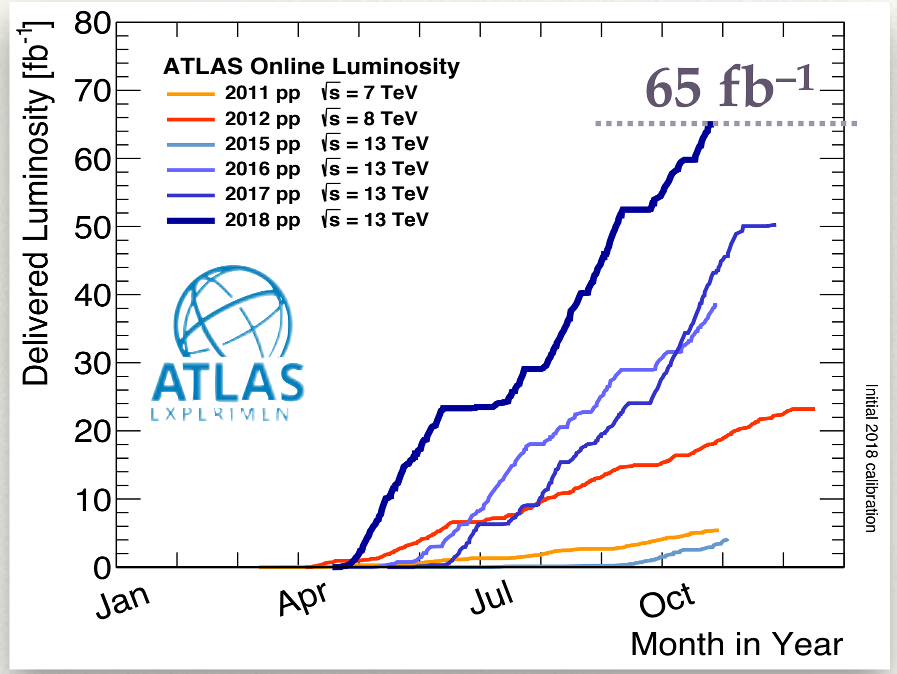
on Higgs & Top

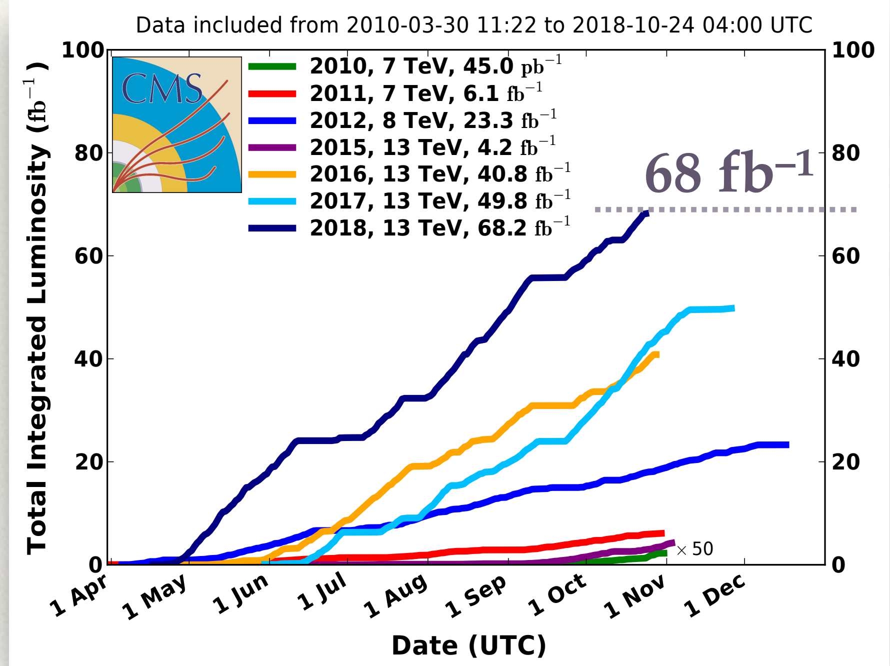
Kai-Feng Chen
National Taiwan University


LHC Page1
Fill: 7334
E: 6499 GeV
t(SB): 13:25:25
24-10-18 06:02:40
PROTON PHYSICS: BEAM DUMP
Energy:
6499 GeV
I(B1):
1.64e+09
I(B2):
3.83e+08
BTVDD.689339.B1
Updated: 06:01:33
BTVDD.629339.B2
Updated: 06:01:33
Comments (24-Oct-2018 06:02:15)
End of Protons Physics Run II
MD4 block starting
Finally!
** No meeting Wednesday morning **
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
true
true
Global Beam Permit
false
false
Setup Beam
false
false
Beam Presence
false
false
Moveable Devices Allowed In
true
true
Stable Beams
false
false
AFS: 25ns_2556b_2544_2215_2332_144bpi_20injV3
PM Status B1
ENABLED
PM Status B2
ENABLED

LHC 2018: Thanks for all the data

- LHC has produced 3 years of high luminosity collisions at 13 TeV and result in **~160 fb^{-1}** in total at the end of the 2018 operation.
  - In 2018 the maximum peak luminosity keeps around 2×10^{34} cm^{-2} s^{-1} with mean pileup interactions around 40.
  - Exceeded peak designed luminosity by a **FACTOR OF TWO**!
  - Thanks to the rapid turn-around between the fills, The availability of LHC is also much higher than the expectation, with >50% of the time in stable operation.



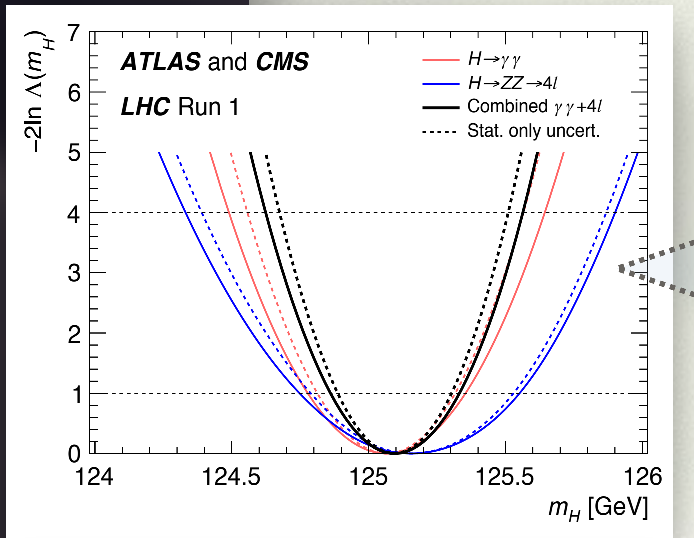


WILL TAKE A WHILE TO DIGEST ALL THE DATA!

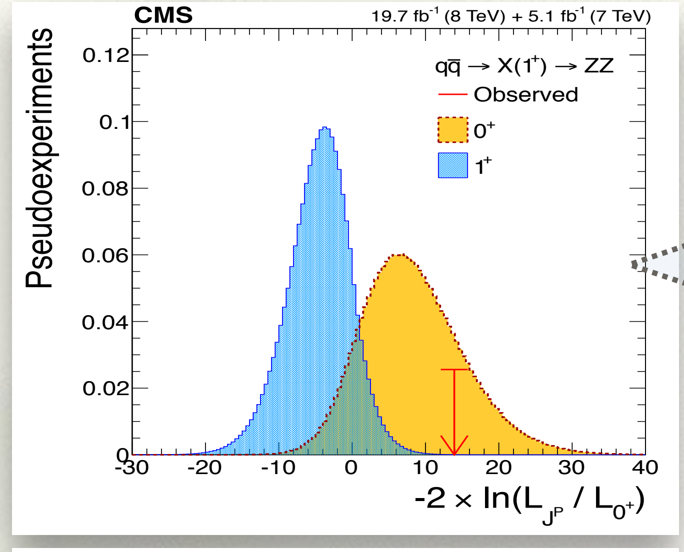
Most of the analyses to date only use the data collected up to 2016, with some exceptional cases go to 2017. *Will have to wait a little bit longer!*

Higgs: What We Have Learned in Run-1?

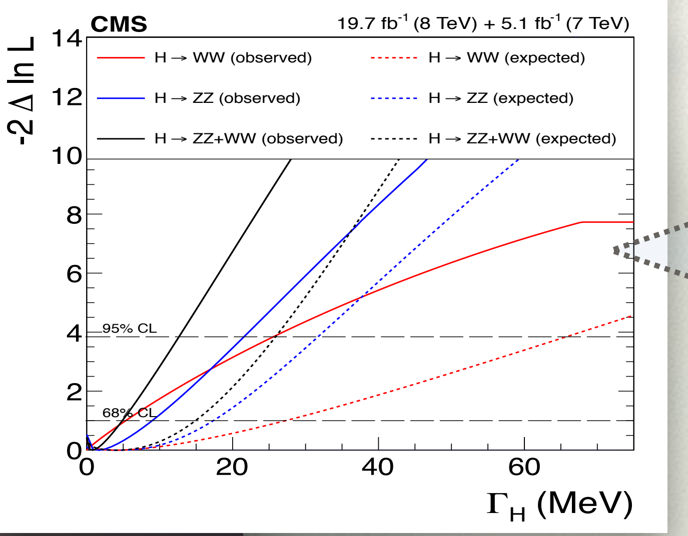
We know its ***existence***, and quite a few properties!



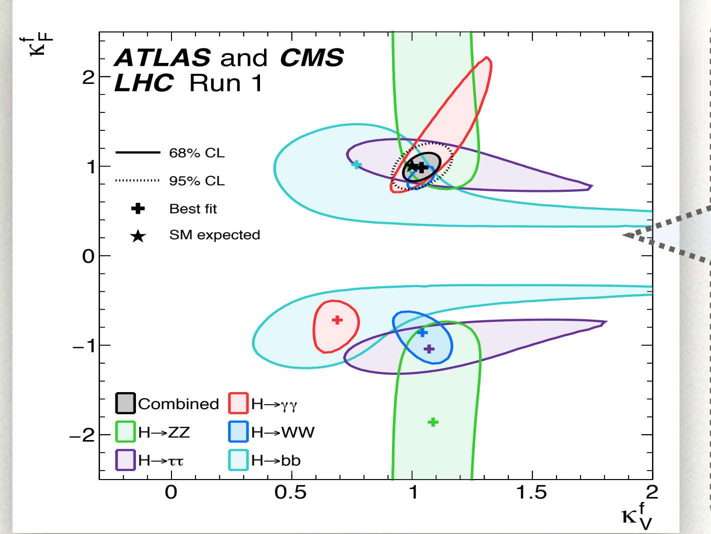
The mass has been measured to be 125.1 GeV, up to a precision of 0.2 GeV.



It has no spin — the only spin less elementary particle so far!



Width < 1 GeV (*direct measurement*); <0.013 GeV (*indirect constraint*)

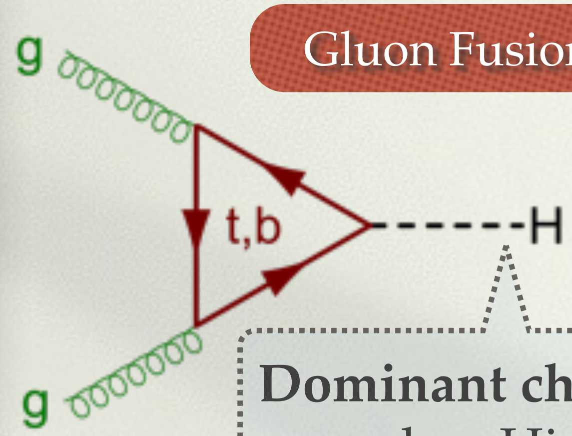


The coupling strengths to other particles do proportion to their masses as in the standard model.

Continue to look for more: (un)expected decays/couplings, multi-Higgs, charged Higgs, anything heavier, etc.

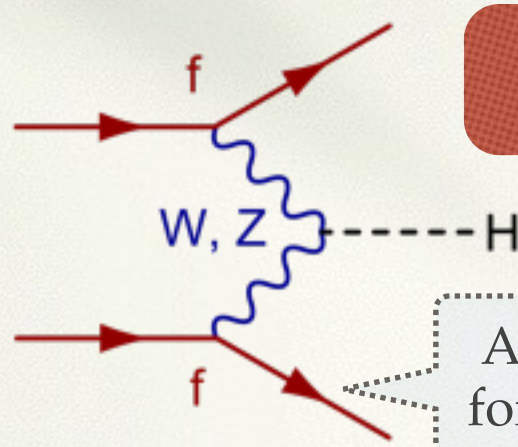
Reminder: Higgs Production & Decay

Gluon Fusion



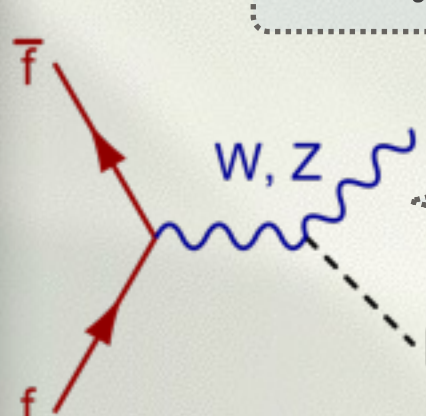
Dominant channel; only a Higgs produced through top loop

Vector-boson Fusion (VBF)



Additional forward jets

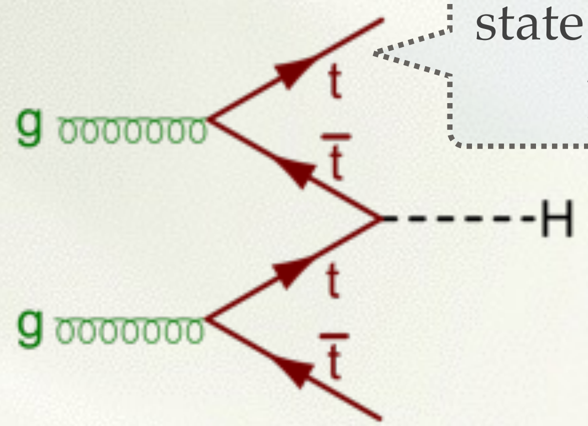
Consider 4 different production & 7 different decays within SM.



Additional W or Z

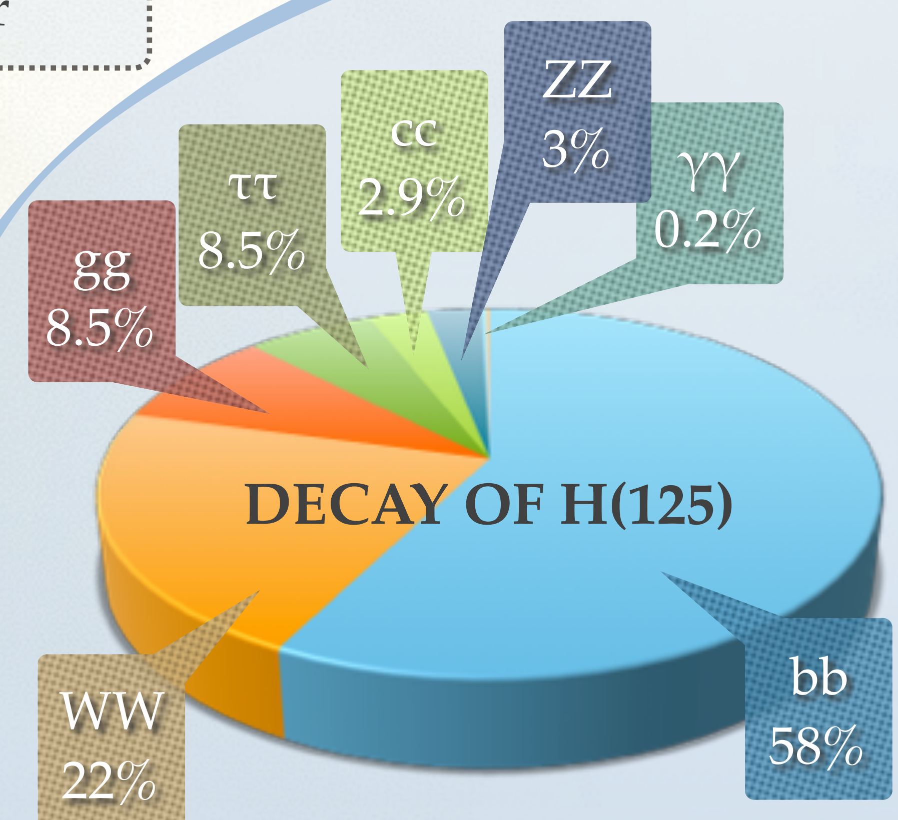
Higgsstrahlung (VH)

Complex final state with top pair



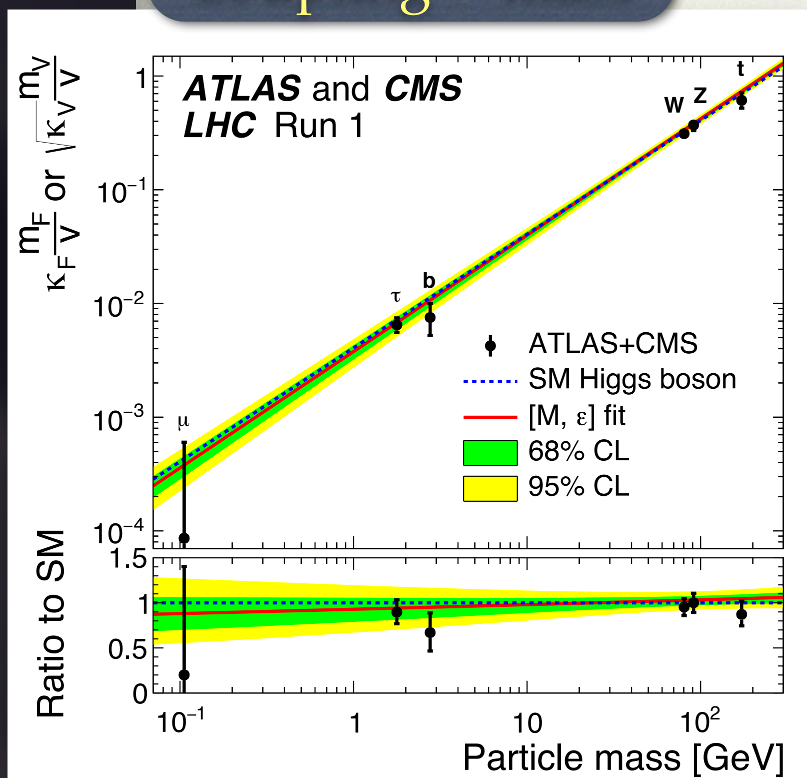
top fusion (ttH)

The actual analyses setup depends on both production and decay (*and background level*).

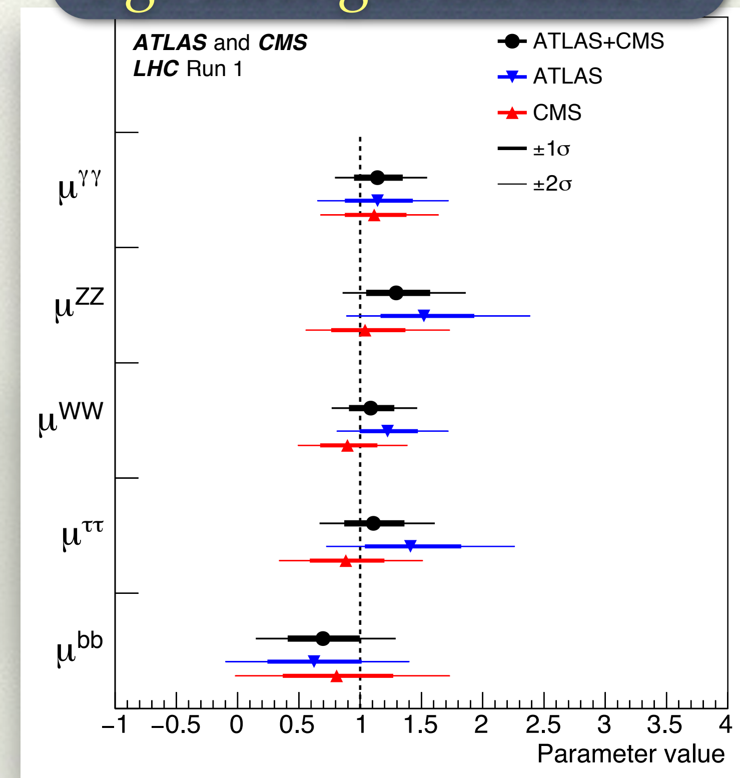


Run-1 Legacy: CMS+ATLAS Combination

Coupling ∝ mass



Sgl. Strength modifiers



		Obs. (Exp.) Significance
Production	VBF	5.4σ (4.6σ)
	VH	3.5σ (4.2σ)
	ttH	4.4σ (2.0σ)
Decay	H→ττ	5.5σ (5.0σ)
	H→bb	2.6σ (3.7σ)

To be discovered!

- Almost all of the properties of the newly discovered boson **consist with the SM expectations**:

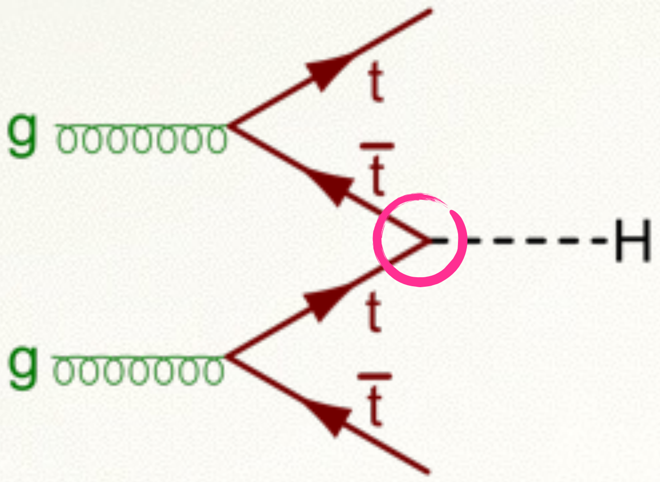
Global signal strength:

$$\mu = 1.09 \pm 007_{(stat)} \pm 0.04_{(expt)} \pm 0.03_{(thbgd)} {}^{+0.07}_{-0.06}{}_{(thsig)}$$

The Run-1 Legacy Paper:
JHEP 1608 (2016) 045 w/ 5153 authors, cited by >800 times already.

Search for ttH Production

- A probe to the **top-Higgs** coupling:
  - through the gluon fusion process, assumes no BSM particles running in the loop
  - through the associated ttH production directly at the tree level.
- Good at Run-2: cross section increases by **3.9x**.



Higgs decay	Branching fraction
H→bb	58%
H→ττ	6.3%
H→ZZ	2.6%
H→WW	22%
H→γγ	0.23%

Reconstruct top pair in all possible channel, with H→bb/ττ in addition.

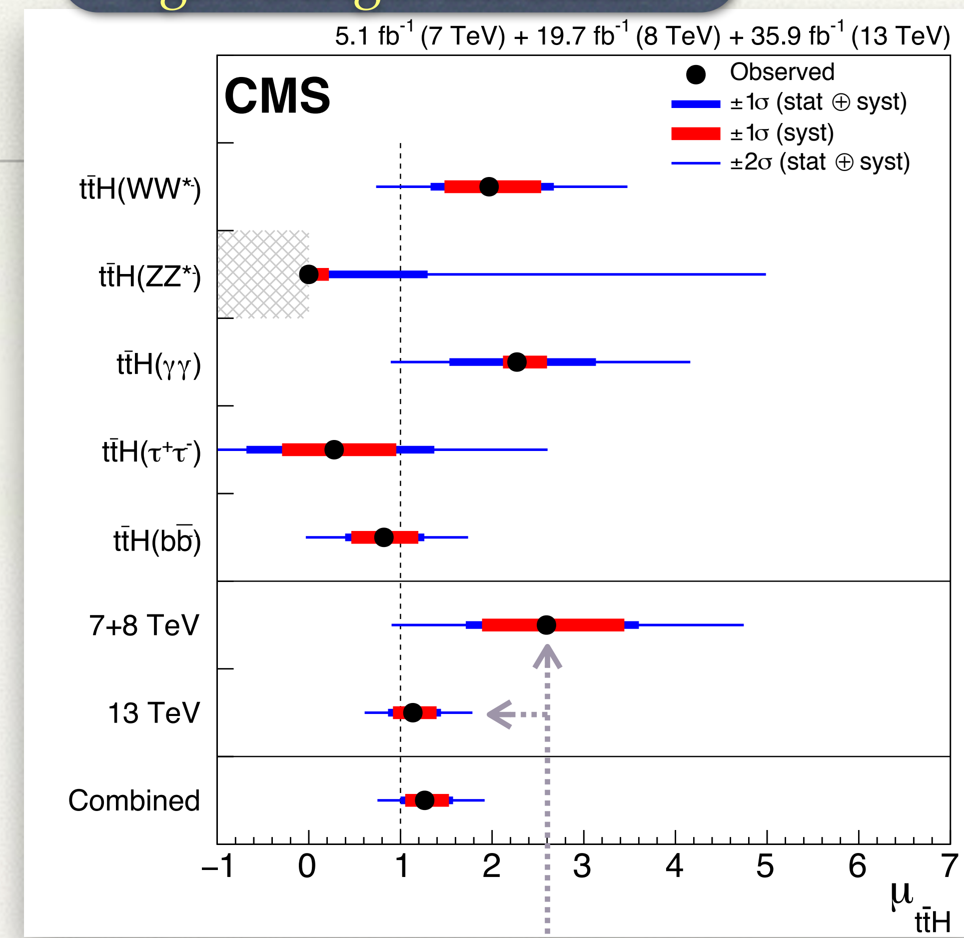
Complex multilepton final state, look for 2-4 leptons + 2 jets (and b-tagged jet)

Low branching fraction but with narrow H→γγ peak.

CMS ttH Results

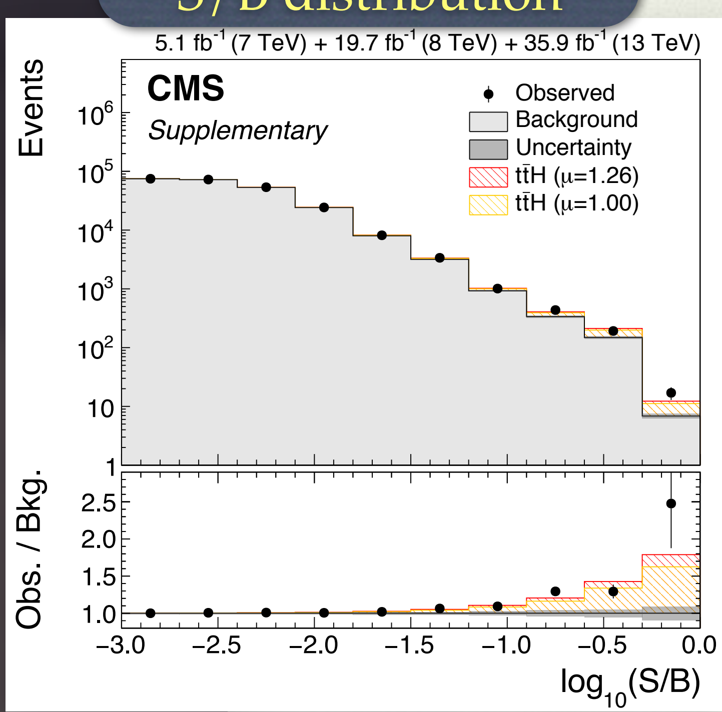
- CMS study of ttH production with combining of all accessible Higgs decays and full run1 + 2016 run2 data.
- **Observation of ttH production**:

Sgl. Strength modifiers

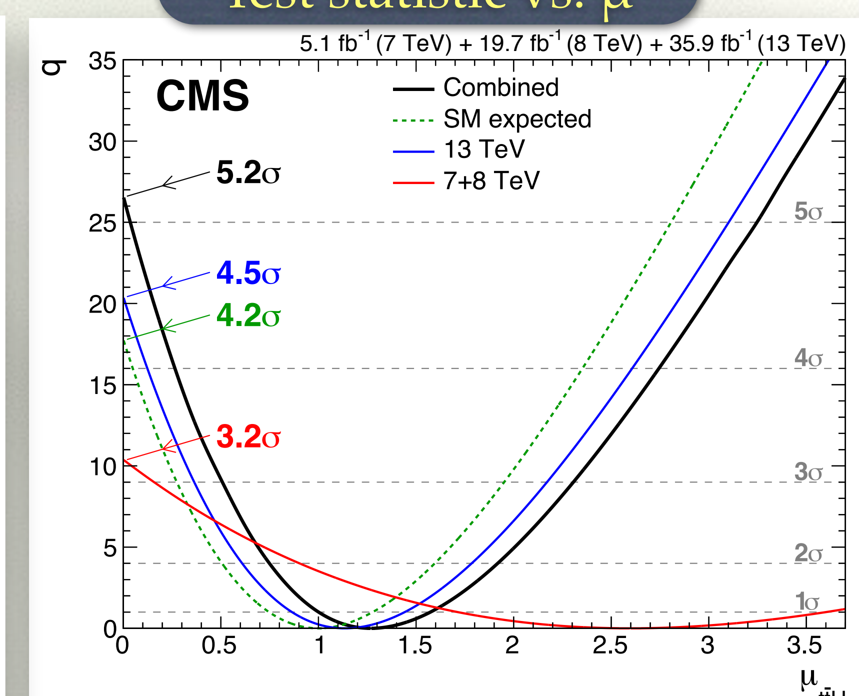


The found excess at Run-1 did not continue at Run-2; now the result is quite SM-like.

S/B distribution



Test statistic vs. μ



Ref. PRL 120 (2018) 231801

Combined result:

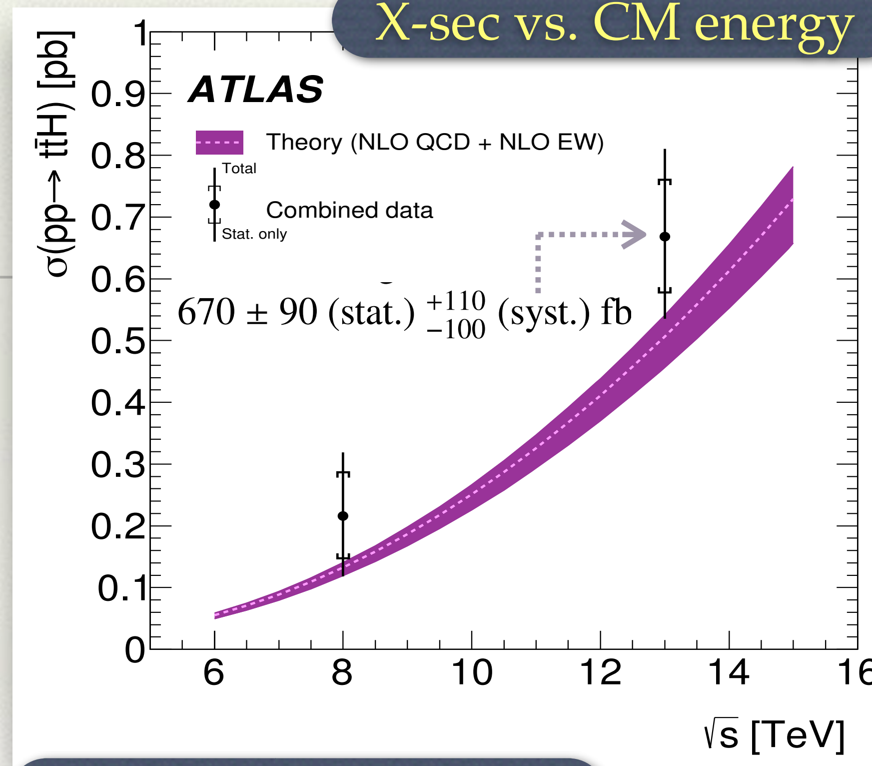
$\mu = 1.26^{+0.31}_{-0.26}$ (7+8+13 TeV)

obs. (exp.) significance: 5.2σ (4.2σ)

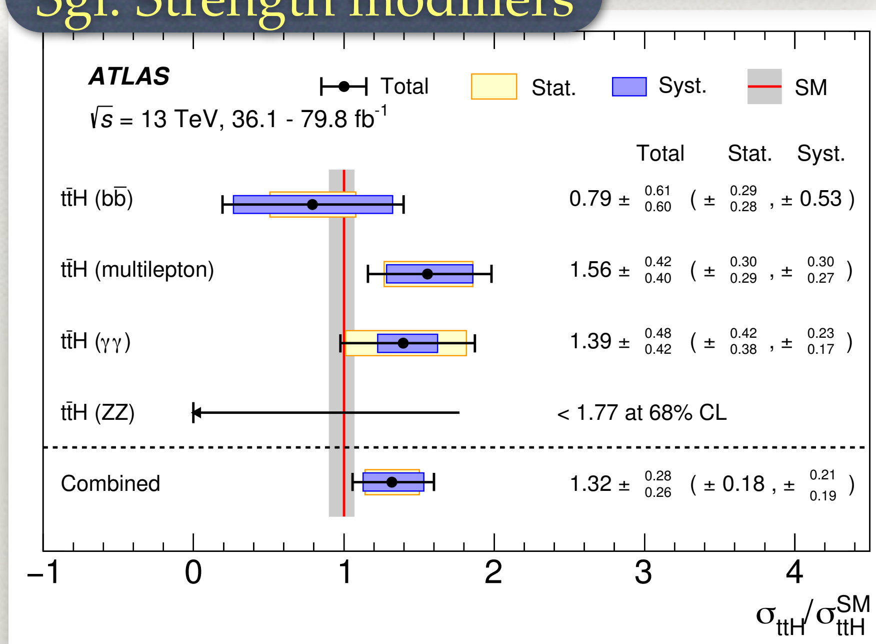
ATLAS ttH Results

- ATLAS measure ttH production with 13 TeV 2016 (and 2017) data, and combining with Run-1 samples for the discovery significance.
- **Observation of ttH production**. Mild excess but still agrees with SM expectations.

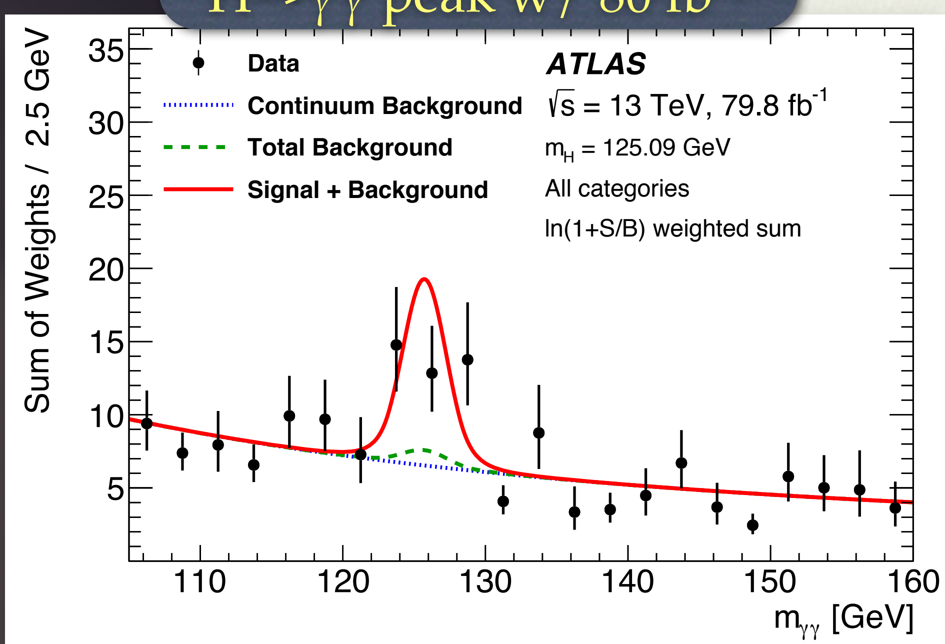
X-sec vs. CM energy



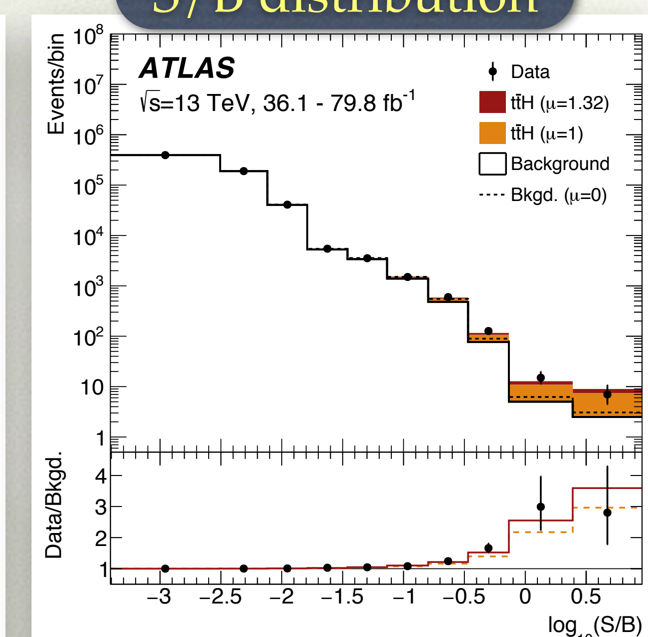
Sgl. Strength modifiers



H→γγ peak w/ 80 fb⁻¹



S/B distribution



Ref. PLB 784 (2018) 173

$\mu=1.32^{+0.28}_{-0.26}$ (13 TeV only)

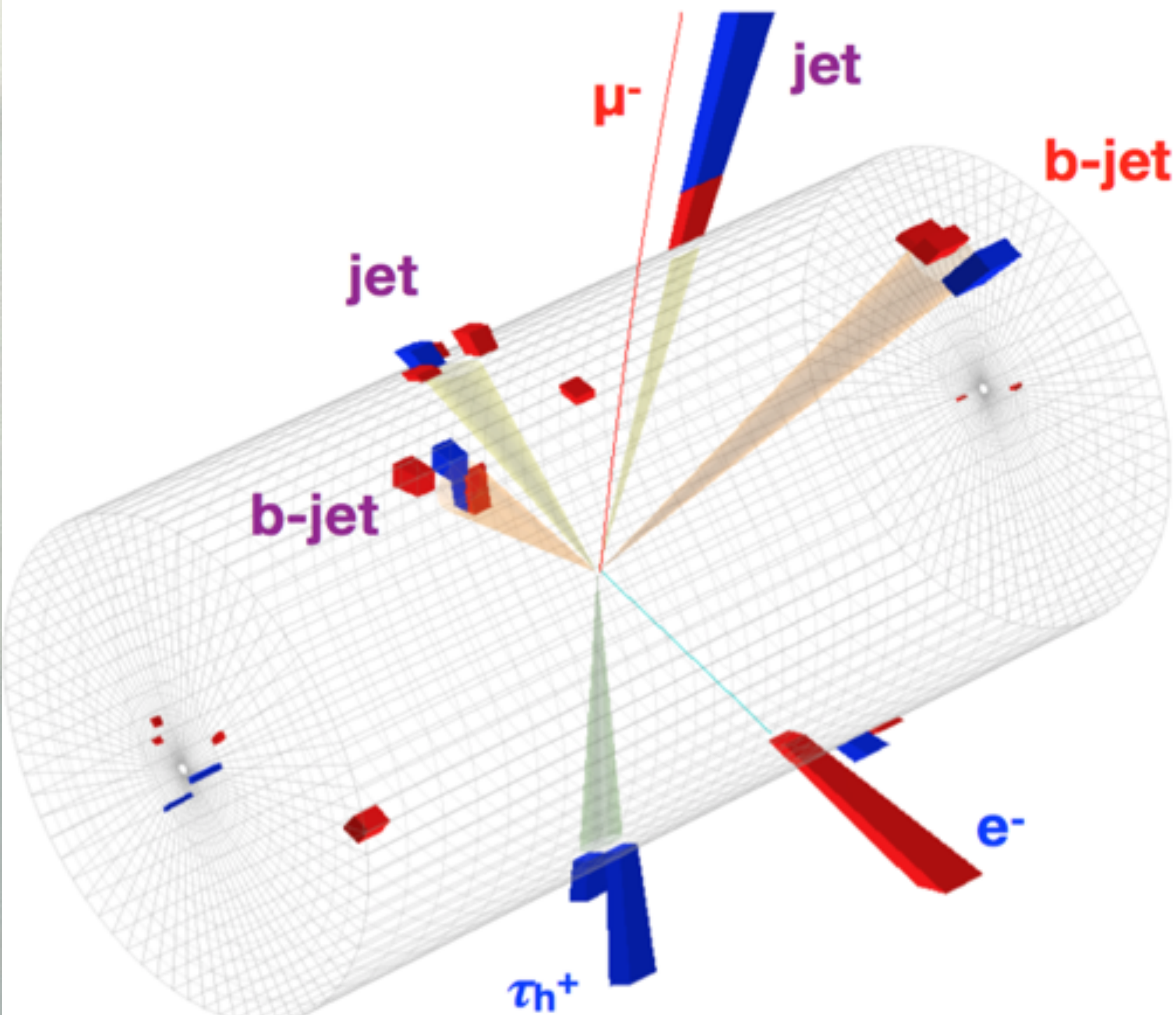
obs. (exp.) significance: 5.8σ (4.9σ)

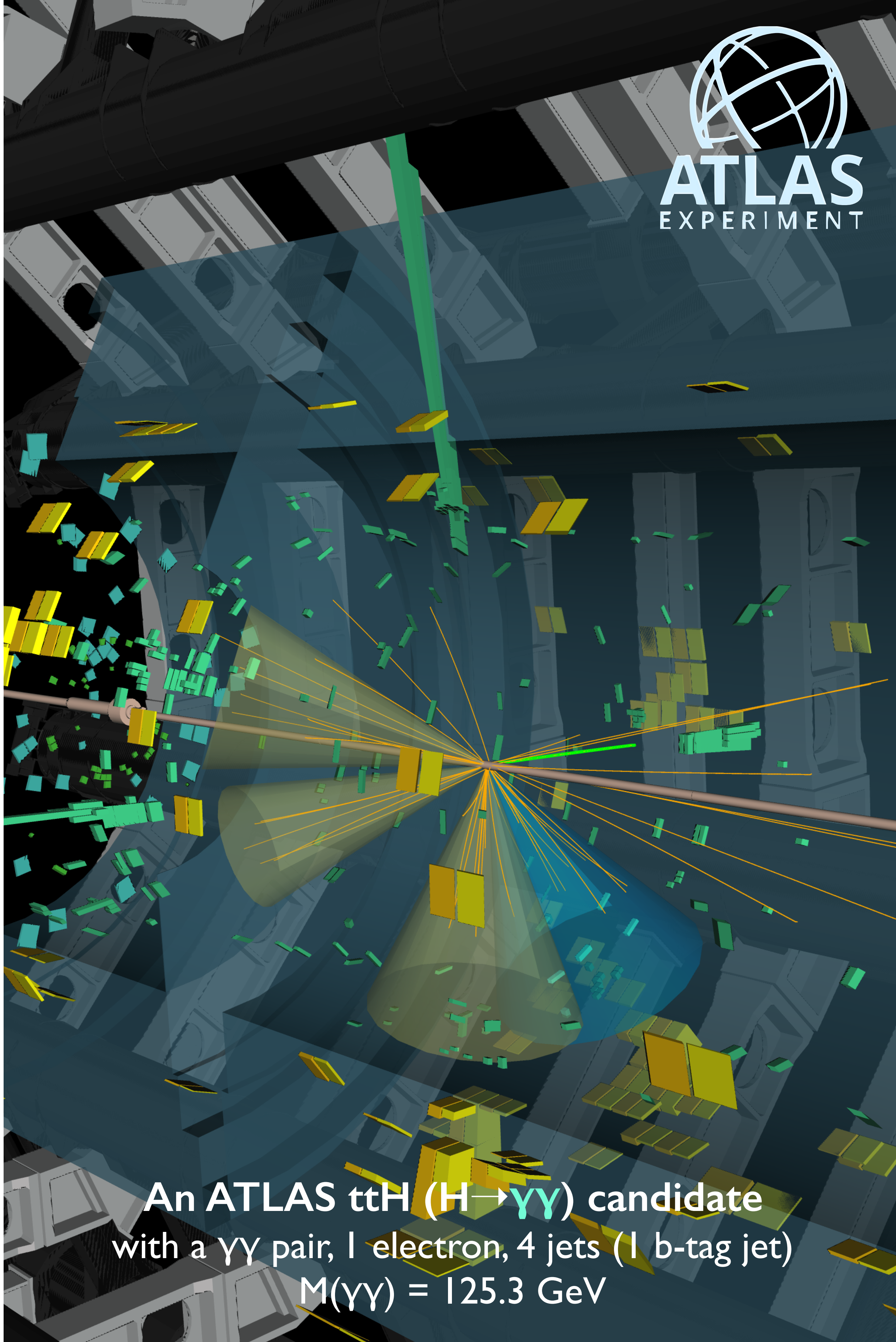
+Run1: 6.3σ (5.1σ)

A CMS ttH (H→ττ) candidate

$$pp \longrightarrow t\bar{t}H$$

- $\tau\bar{\tau} \longrightarrow e^- + \bar{\nu}_e + \nu_\tau + \tau_h^+ + \bar{\nu}_\tau$
- $\bar{b}W^- \longrightarrow \bar{b} + \mu^- + \bar{\nu}_\mu$
- $bW^+ \longrightarrow b + q + q$

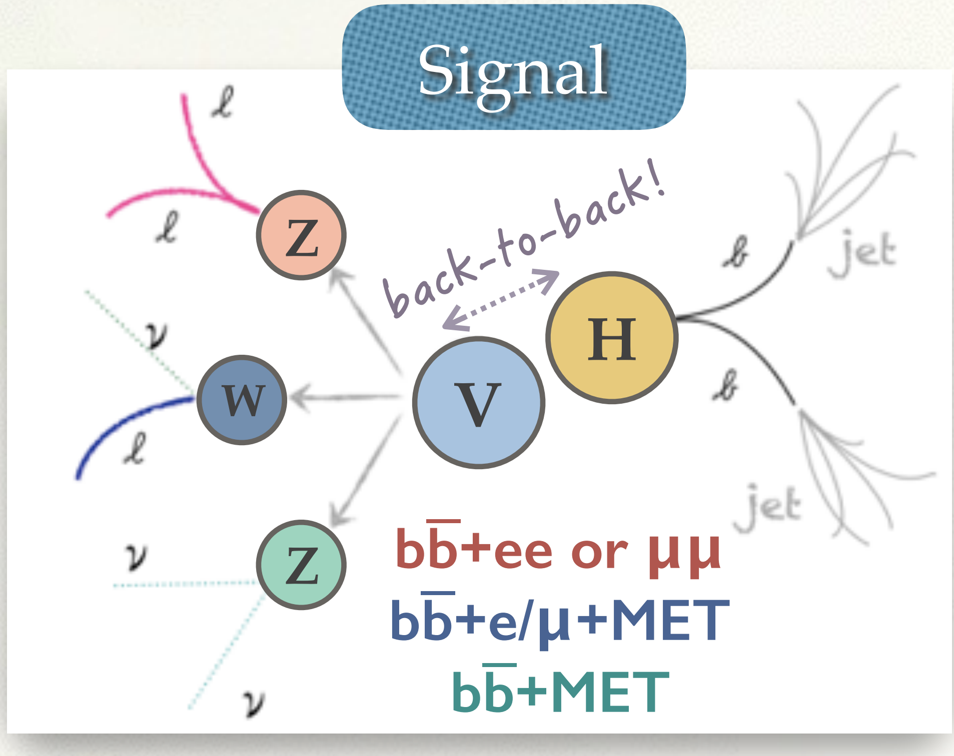


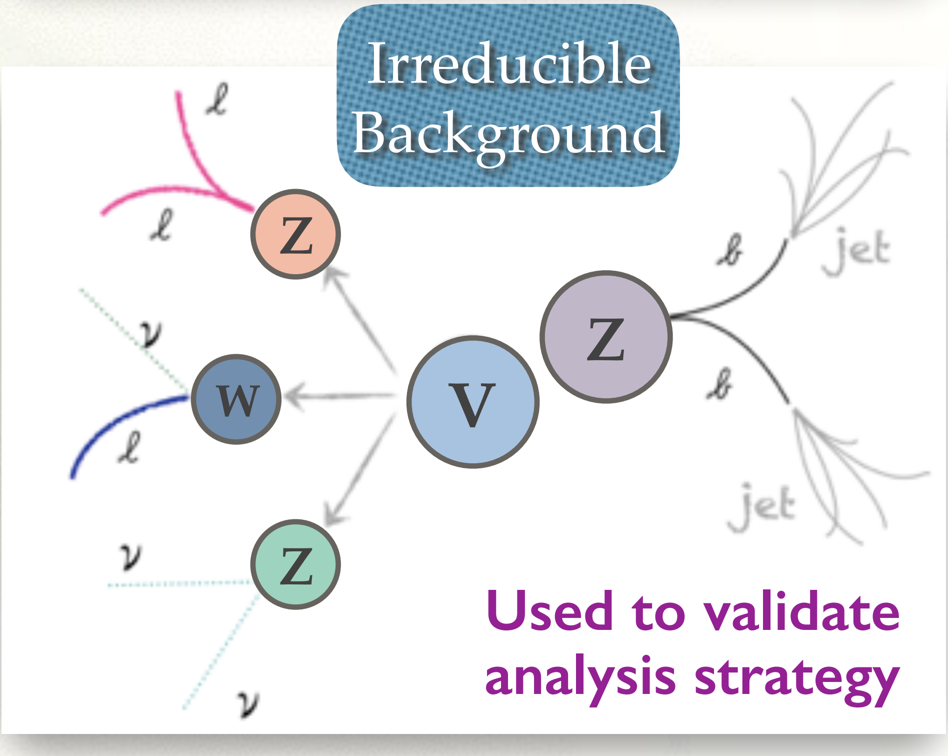


An ATLAS ttH (H→γγ) candidate
with a γγ pair, 1 electron, 4 jets (1 b-tag jet)
M(γγ) = 125.3 GeV

Measurement of H→b$\bar{b}$ Decay

- The decay with the largest branching fraction but it is also a very difficult channel.
- Main challenge from the **MASSIVE b$\bar{b}$ background from QCD processes**, ~10^3 times to the signal in the target mass region.
- Choose the production signature associated with a W or Z, a.k.a. the **VH production** to reduce the background.
- Heavily rely on b-tagging and multivariate analysis, too!



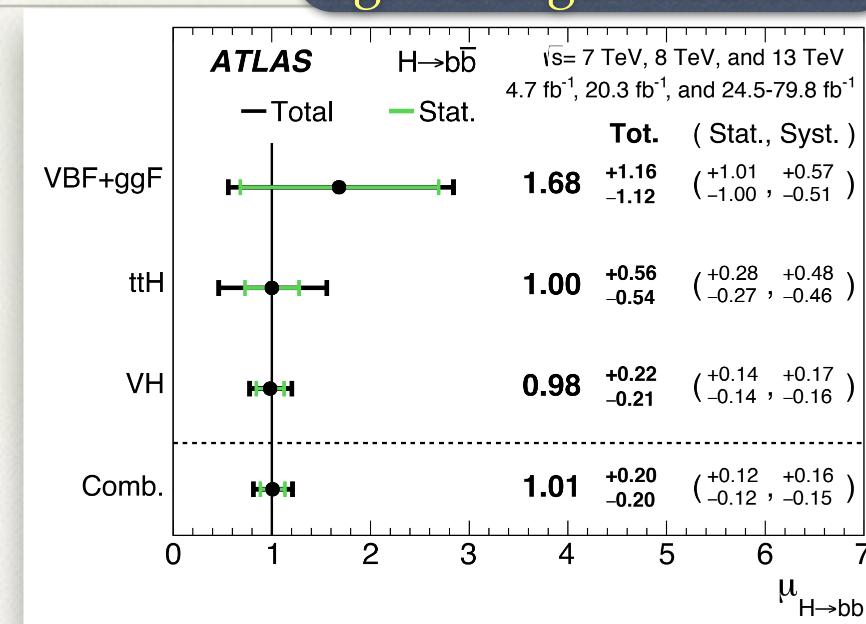


ATLAS H→b$\bar{b}$ Result

Ref. PLB 786 (2018) 59

- ATLAS study of H→b$\bar{b}$: Multivariate analysis in 0,1 and 2 lepton channels.
- Cross-checked with diboson VZ; result consists with SM (μ=1.20+0.20/−0.18).
- Combined with other production processes: **observation of H→b$\bar{b}$**; combined with other Higgs decays: **observation of VH production**.

Sgl. Strength modifiers



VH, H→b$\bar{b}$ (run1+2016+2017)

$\mu=0.98^{+0.22}_{-0.21}$

obs. (exp.) significance: 4.8σ (4.9σ)

Combined with VBF/ggF/ttH, H→b$\bar{b}$

$\mu=1.01 \pm 0.20$

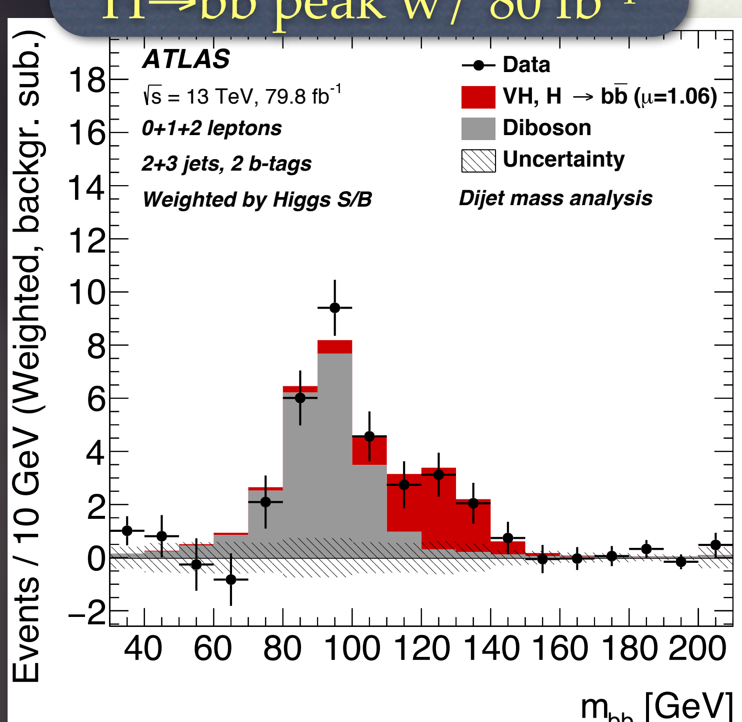
obs. (exp.) significance: 5.4σ (5.5σ)

Combined w/ other Run-2 VH analyses

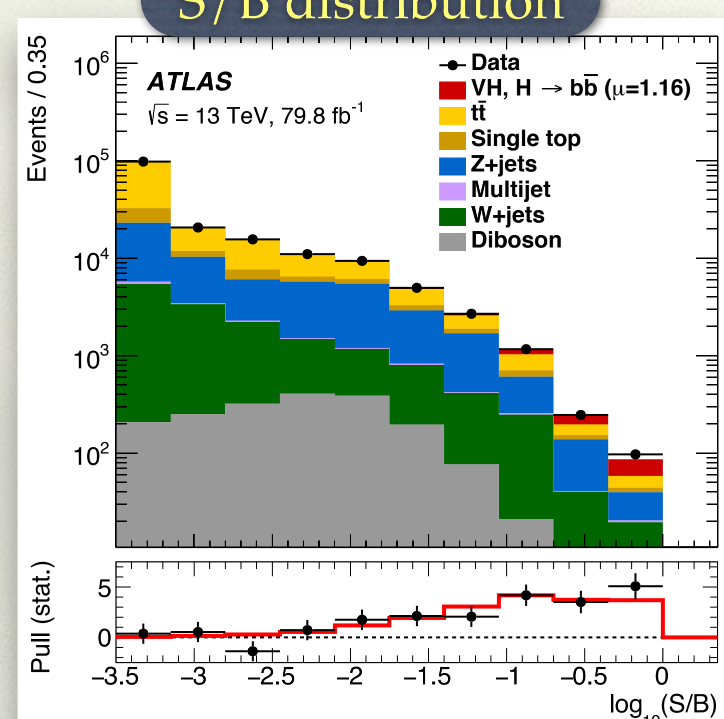
$\mu=1.13^{+0.24}_{-0.23}$

obs. (exp.) significance: 5.3σ (4.8σ)

H→b$\bar{b}$ peak w/ 80 fb^{-1}



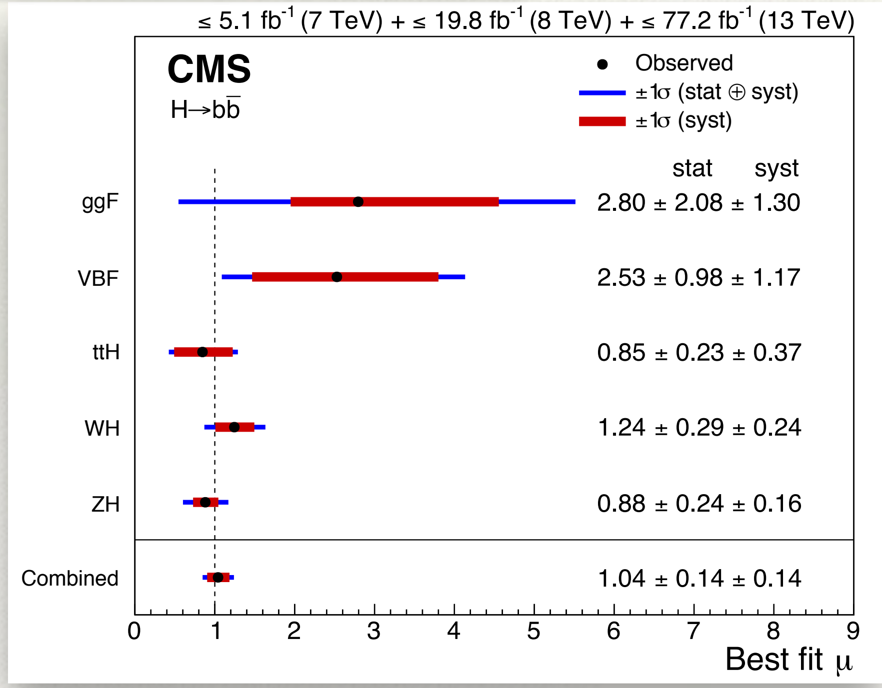
S/B distribution



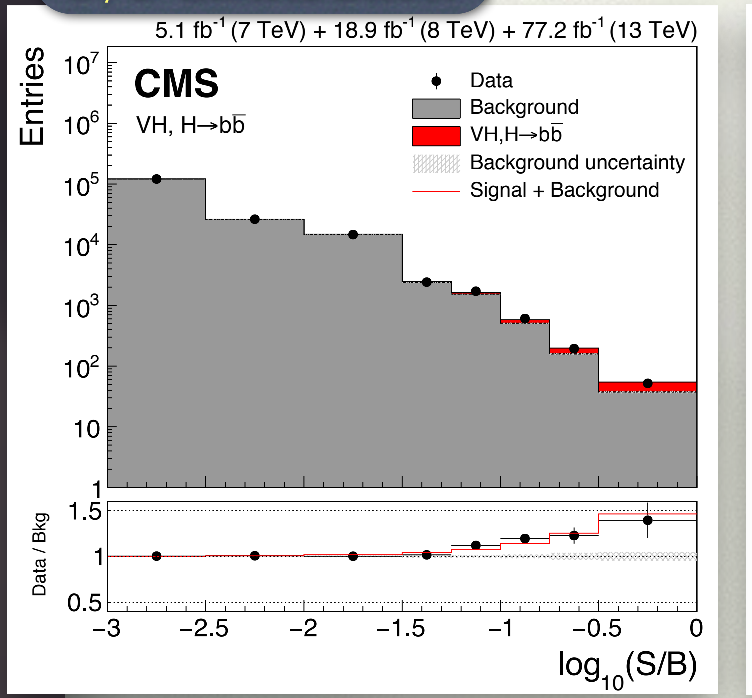
CMS H→b$\bar{b}$ Result

- 3 reconstructed channels (0/1/2 leptons) with improved b-tagging and new b-jet energy regression.
- Cross checked with VZ(→b$\bar{b}$), consistent with SM (μ=1.05±0.22).
- Nearly observation of VH production; combined with other processes confirm the **observation of H→b$\bar{b}$** with full Run1+2016(+2017) data sets.

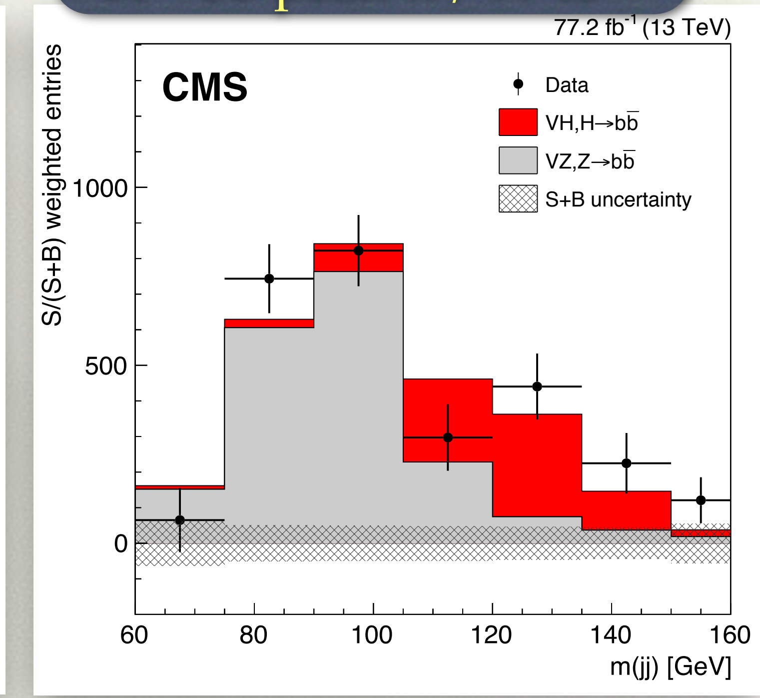
Sgl. Strength modifiers



S/B distribution



H→b$\bar{b}$ peak w/ 77 fb^{-1}



Ref. PRL 121 (2018) 121801

VH, H→b$\bar{b}$ (run1+2016+2017)

μ=1.01 ± 0.22

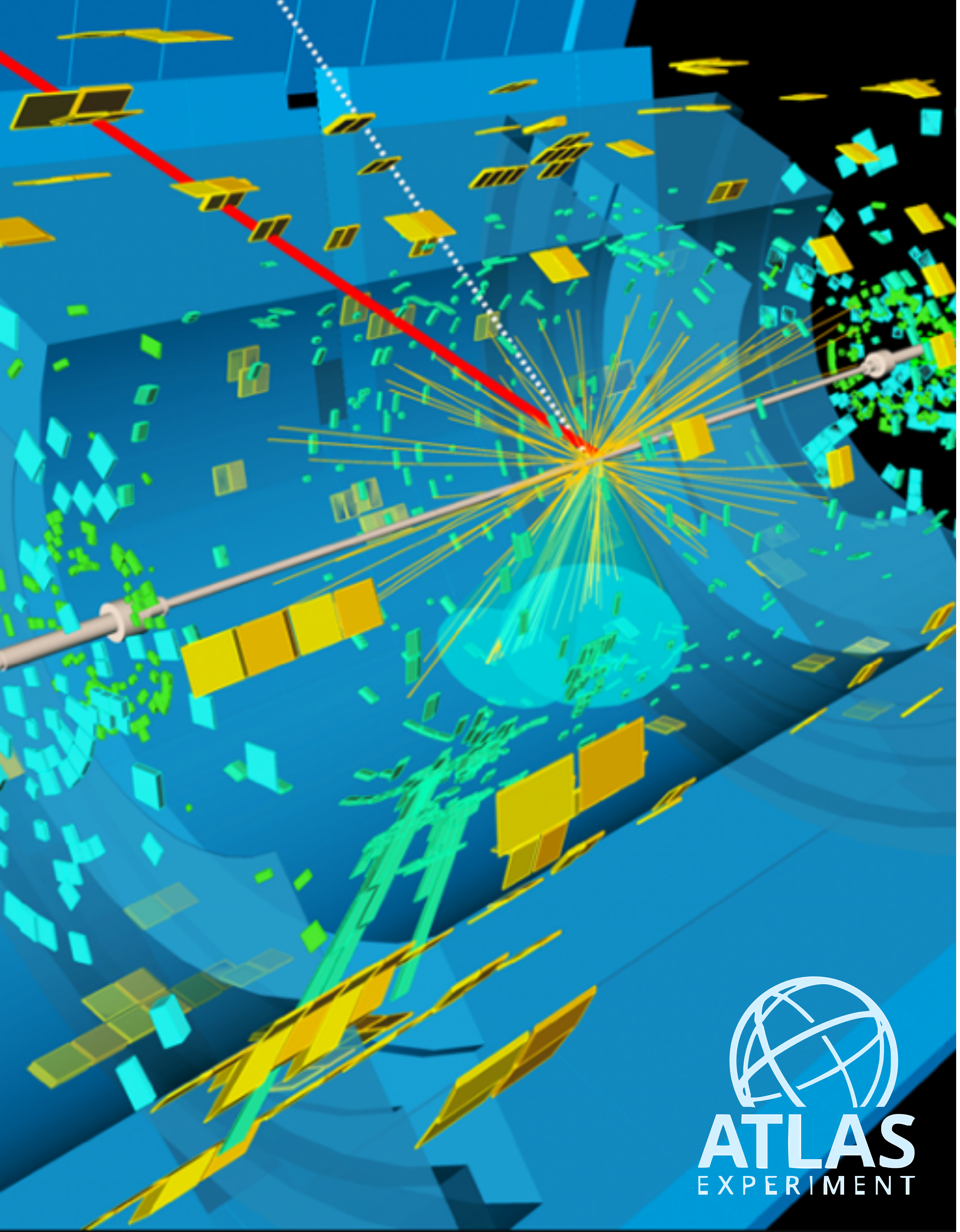
obs. (exp.) significance: 4.8σ (4.9σ)

Combined with other productions

μ=1.04 ± 0.20

obs. (exp.) significance: 5.6σ (5.5σ)

An ATLAS WH ($W \to \mu\nu$, $H \to bb$) candidate event collected in 2017

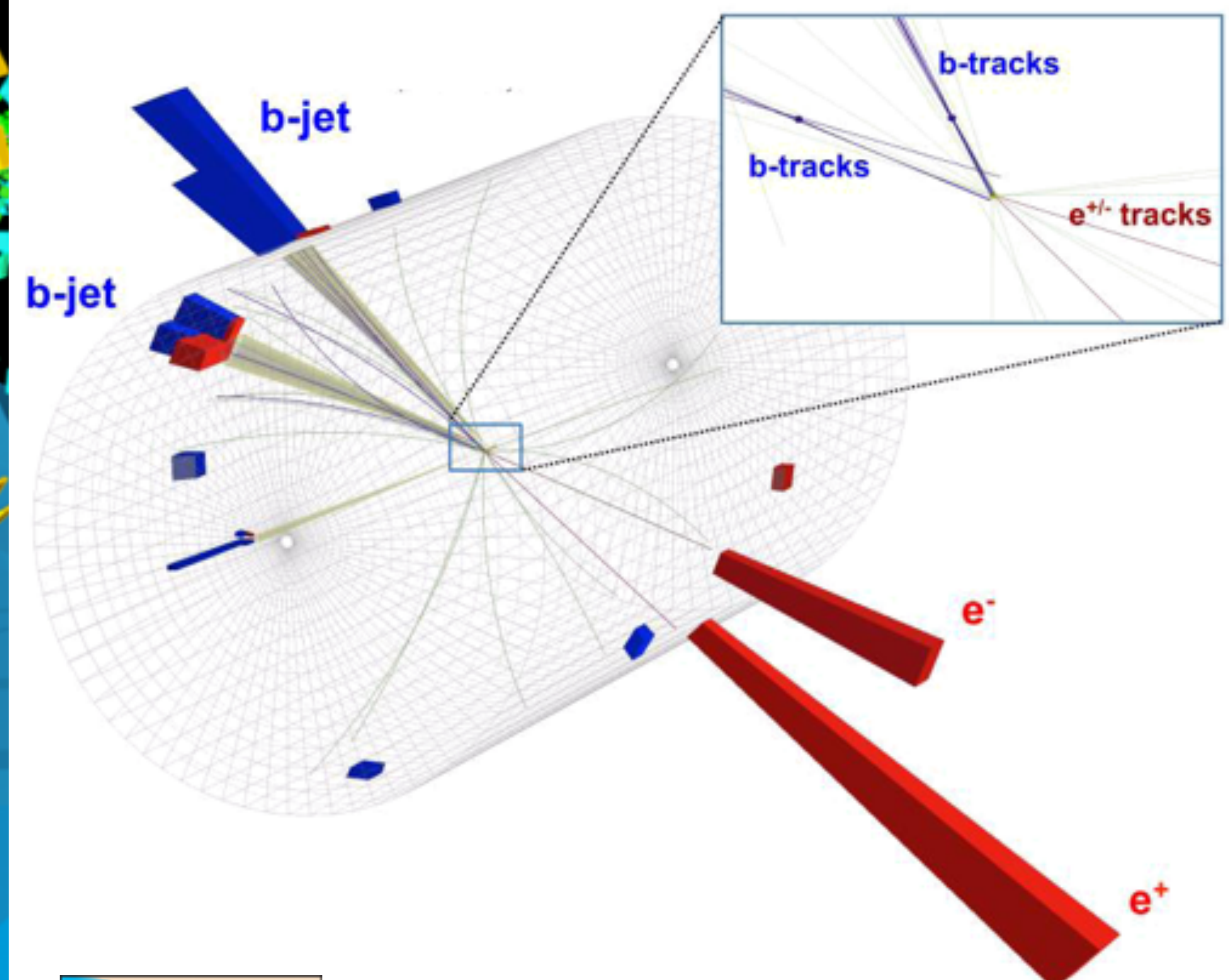


A CMS ZH ($H \to bb$) candidate event collected in 2017

$pp \to ZH$

$Z \to e^+ + e^-$

$H \to b + \bar{b}$



Remark: these events are just "candidates", since there are still lots of background!

More Higgs Studies

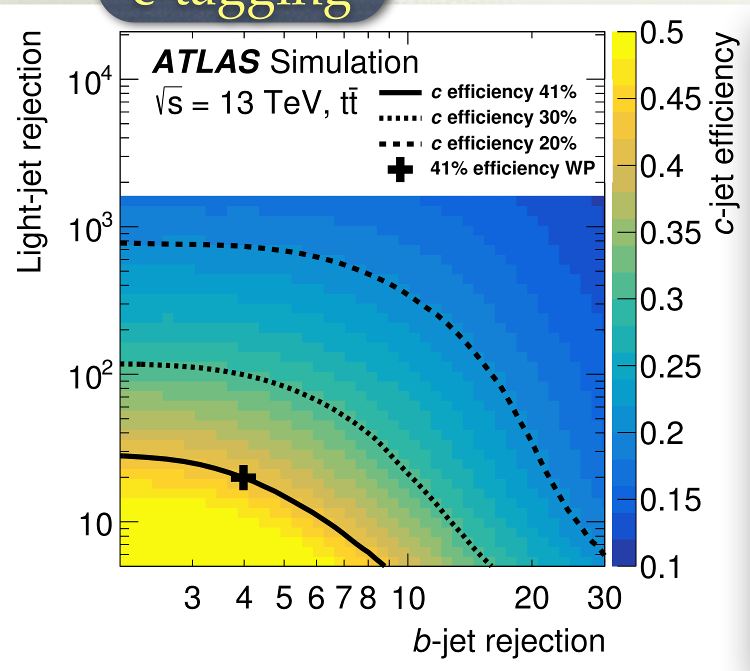
How about Higgs coupling to the second generation?

- ATLAS search of $H \to c\bar{c}$ with 2016 data:

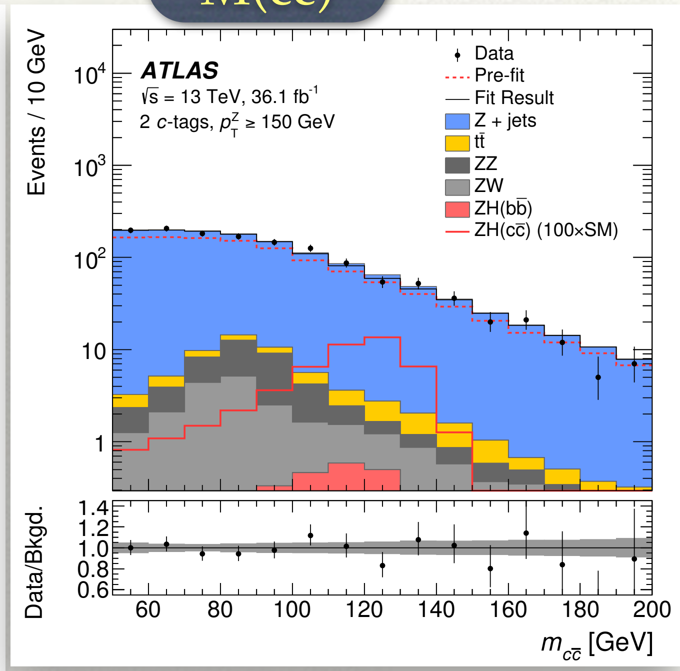
$\sigma(ZH)\times BF(H \to c\bar{c}) < 2.7$ pb
or $\mu < 110$ @ 95% C.L.

Ref. PRL 120 (2018) 211802

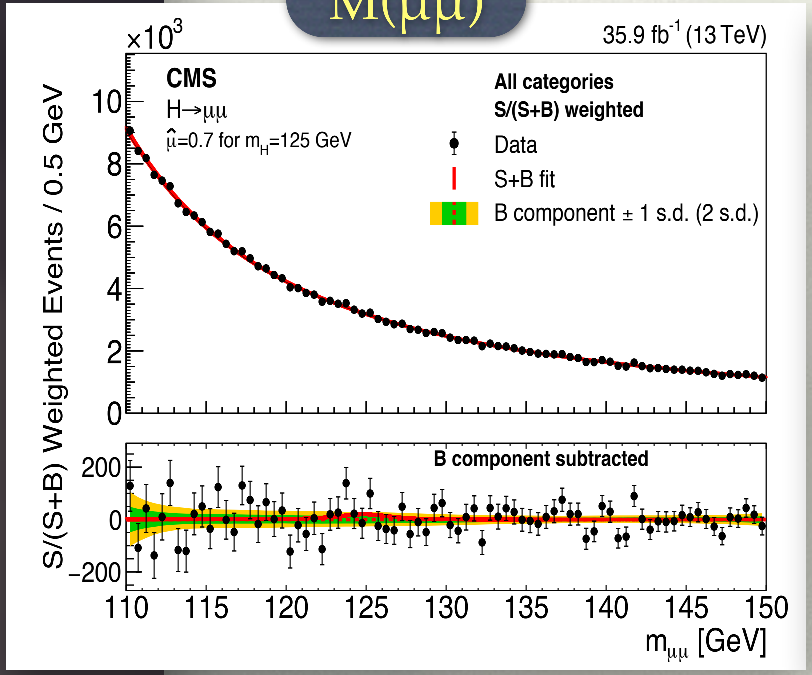
c-tagging



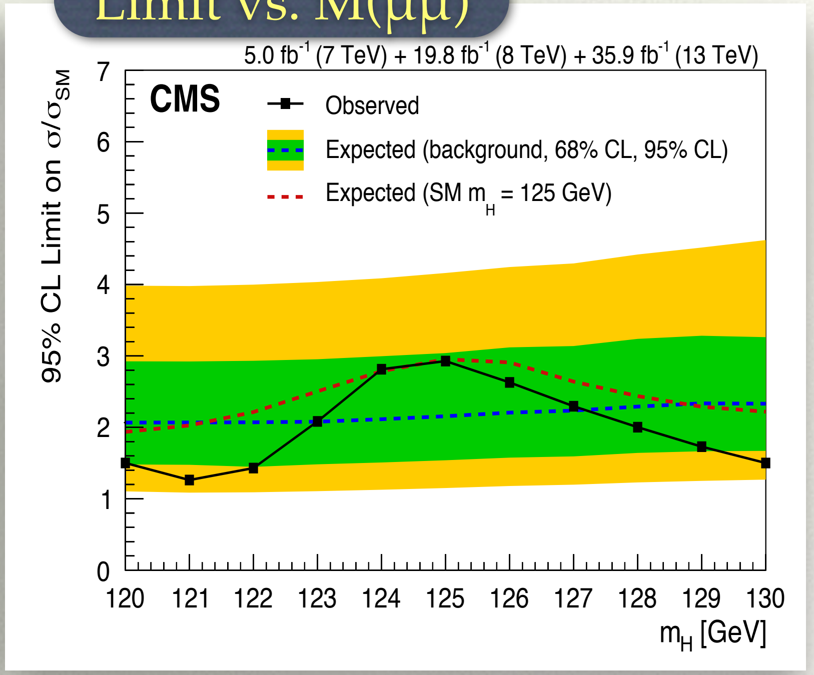
M(cc̄)



M(μμ)



Limit vs. M(μμ)



- CMS search of $H \to \mu^+\mu^-$ with Run1+2016 data:

$BF(H \to \mu^+\mu^-) < 6.4 \times 10^{-4}$
or $\mu < 2.92$ @ 95% C.L.

Ref. arXiv:1807.06325
submitted to PRL

More Higgs Studies (cont.)

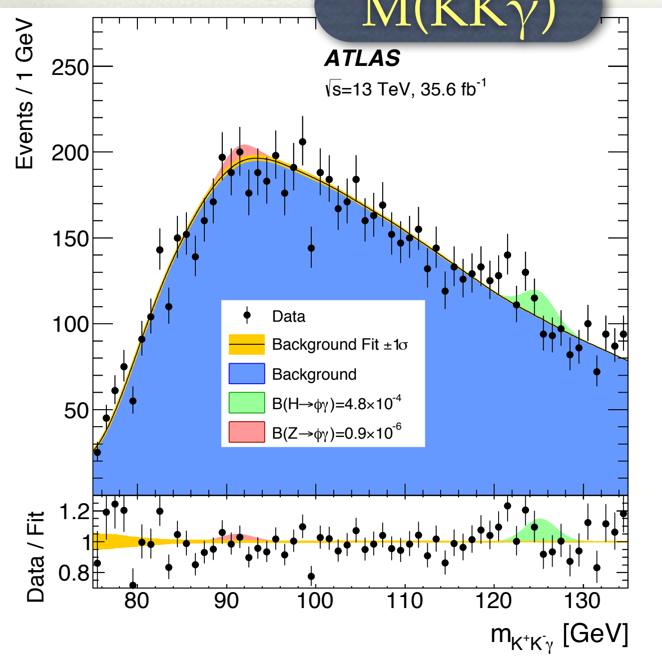
How about something more exotic?

- ATLAS search of H/Z→ϕγ/ργ with 2016 data:

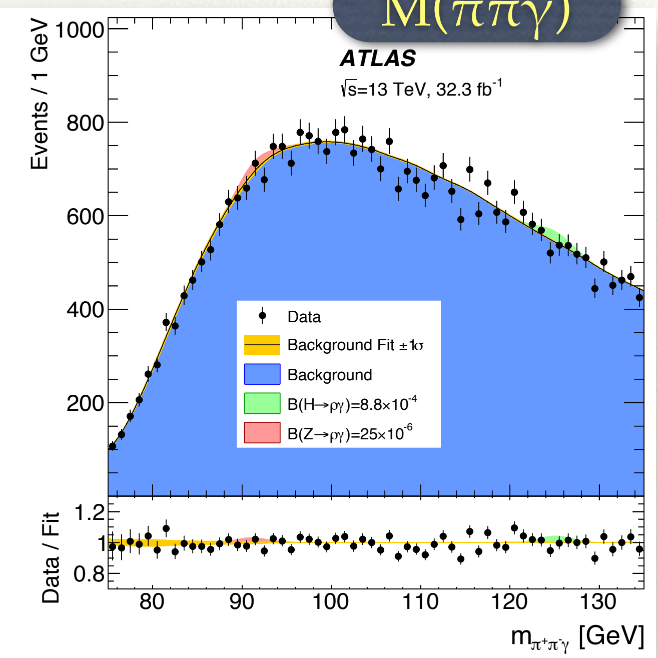
BF(H→ϕγ) < 4.8 × 10⁻⁴
BF(H→ργ) < 8.8 × 10⁻⁴
BF(Z→ϕγ) < 0.9 × 10⁻⁶
BF(Z→ργ) < 2.5 × 10⁻⁵

Ref. JHEP 07 (2018) 127

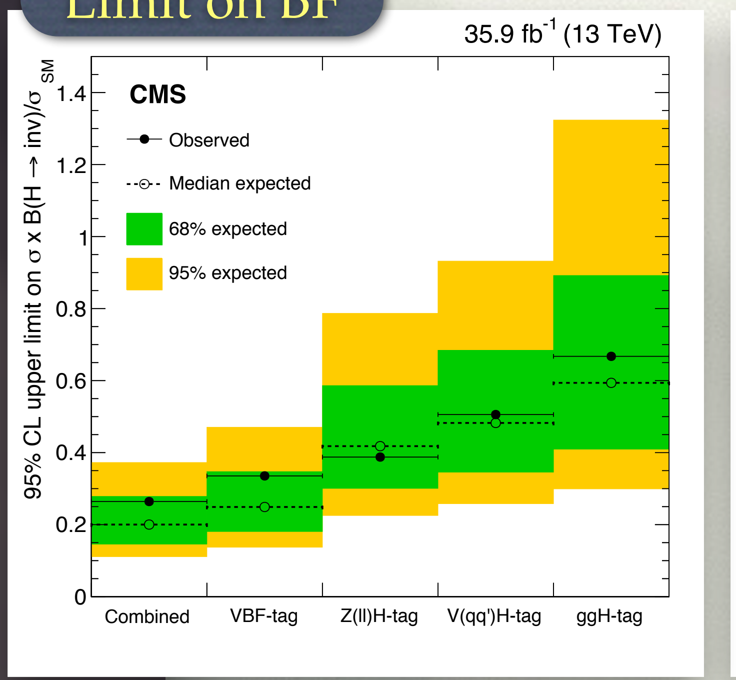
M(KKγ)



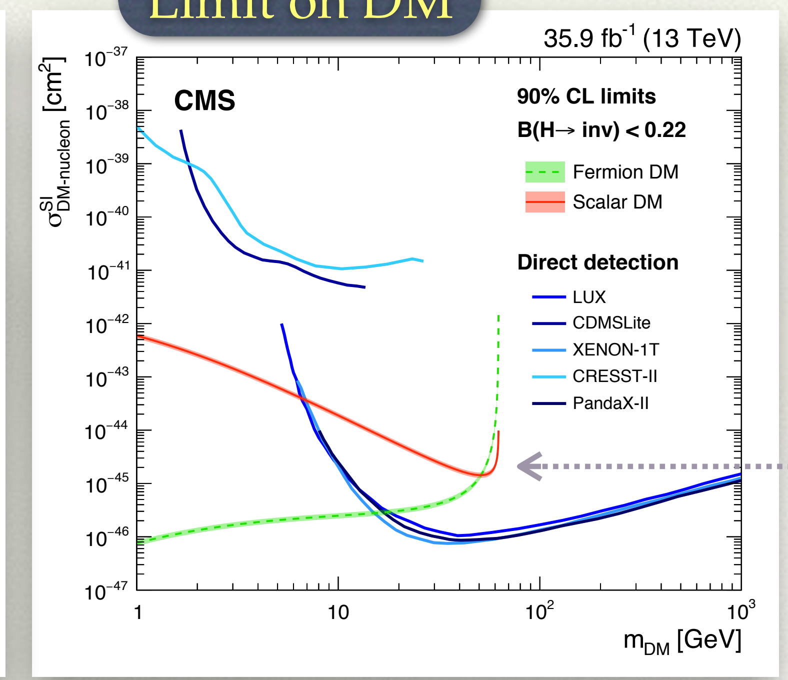
M(ππγ)



Limit on BF



Limit on DM

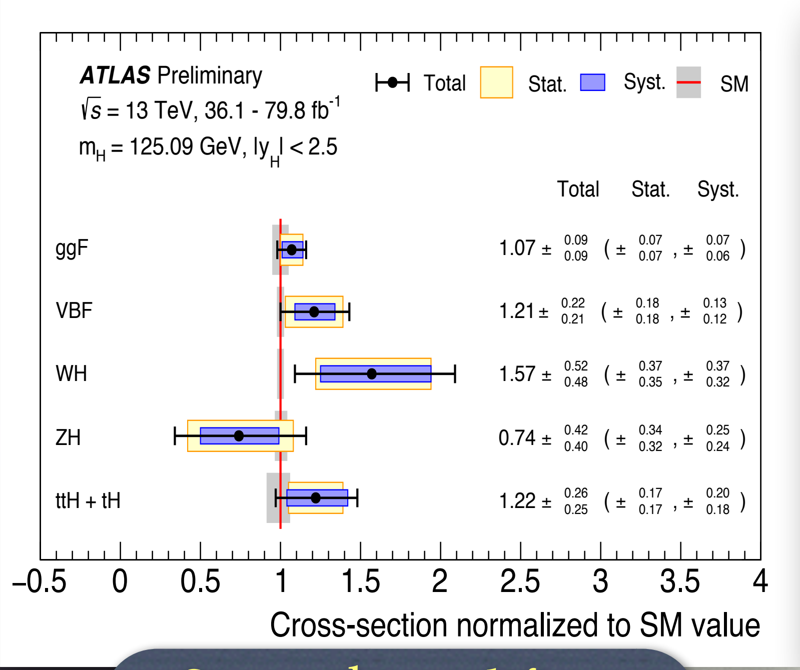


- CMS search of H→invisible with 2016 data:

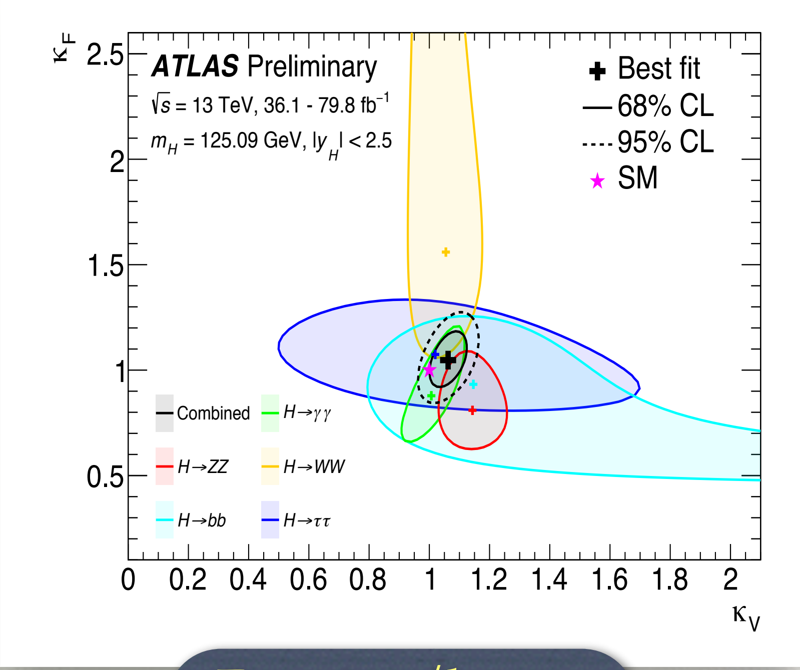
BF(H→invisible) < 26% ***and*** **constraints to Higgs-portal models of DM**

Ref. arXiv:1809.05937
submitted to PLB

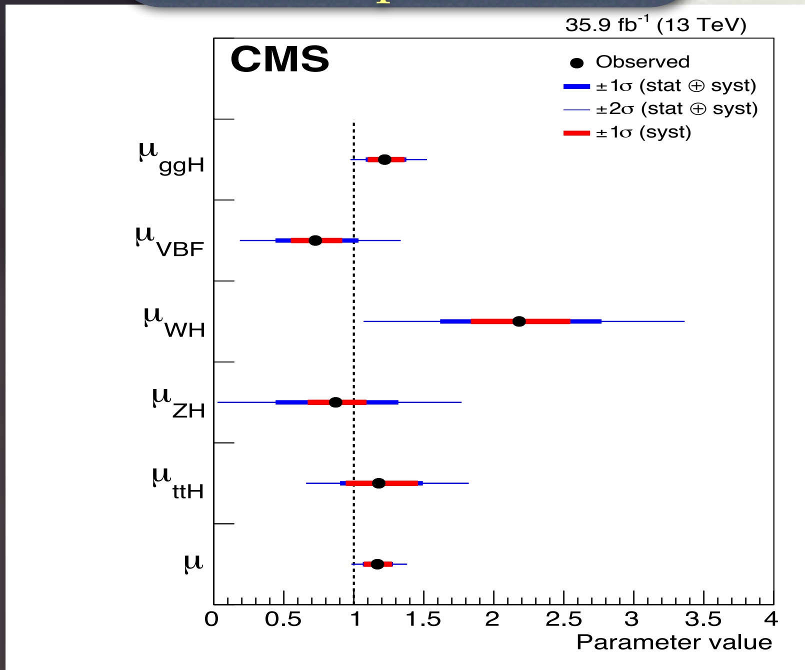
Combination @ 13 TeV

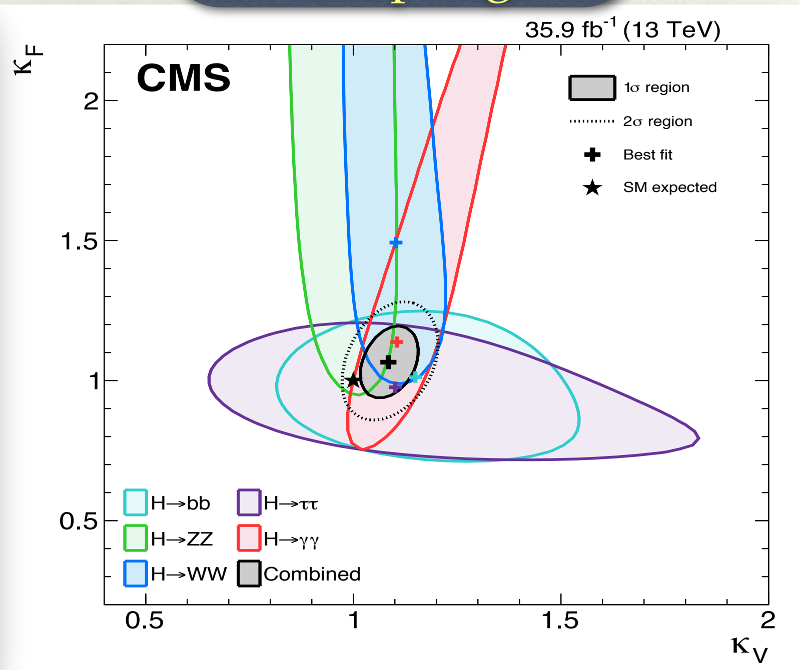


Strength modifiers for each production



Fermion/boson Coupling





- Combination of all Higgs production and decay channels at 13 TeV and check the overall consistency of the couplings:

Ref. ATLAS-CONF-2018-031

ATLAS global strength:

$\mu = 1.13^{+0.09}_{-0.08}$

arXiv:1809.10733, sub. to EPJC

CMS global strength:

$\mu = 1.17 \pm 0.10$

Results are in agreement with the SM still!

Higgs Checklist

TASK	CHECK?
Discovery of the boson itself	✔
Observation of ggF production	✔
Observation of $H \to ZZ^*$ decay	✔
Observation of $H \to \gamma\gamma$ decay	✔
Observation of $H \to WW^*$ decay	✔
Observation of VBF production	✔
Observation of $H \to \tau\tau$ decay	✔
Observation of ttH production	✔
Observation of $H \to bb$ decay	✔
Observation of VH production	✔
$H \to \mu\mu$ decay	?
????	

What's the next?

The Higgs Boson is still pretty much SM-like so far!

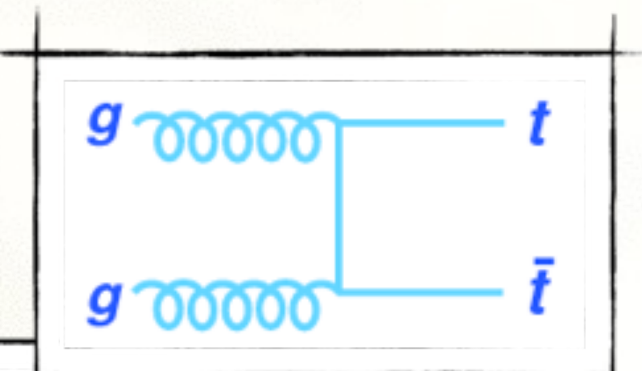
And the excesses fade away with more data...

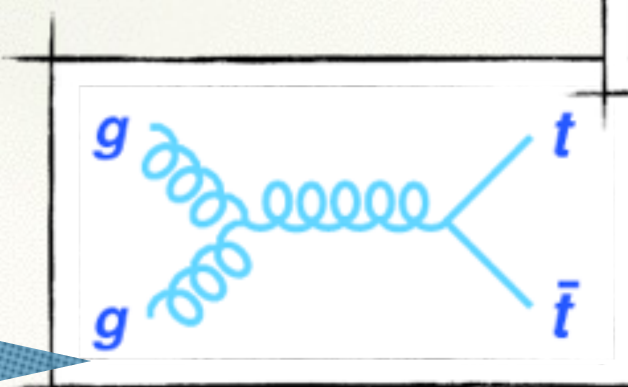
- Only 6 years since the discovery — we already observed / tested many Higgs decays and properties!
- However the Higgs boson is still very unique and requires a lot of further tests, in particular those properties associated with electroweak symmetry breaking…

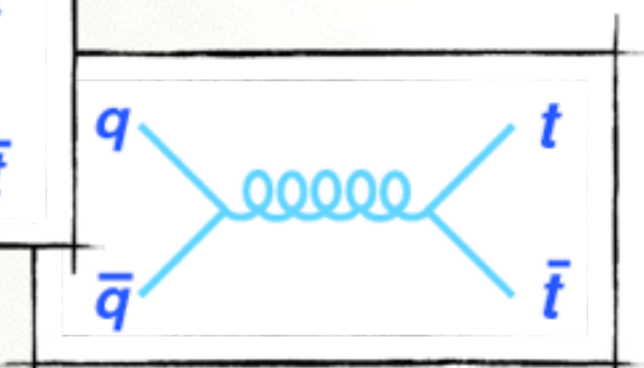
Top Physics @ LHC

- **Precision measurement of top cross section.**
  - Top (pair / single) production rate at high center of mass energy.
- **Large top production rate at LHC — A TOP QUARK FACTORY**
  - Use top quark as a calibration source (*e.g., a very clean source of b-jet*).
  - High precision determination of top quark mass.
  - Test of spin / polarization, asymmetries, etc.
  - Probing electroweak couplings and top rare decays.
- **New physics heavier than the top quark**
  - Heavy new particles decay with (high-p_T) top in the final state.

Top cross section at LHC is ~0.8 nb, not too far from Υ(4S) at B-factory (1.2 nb)!

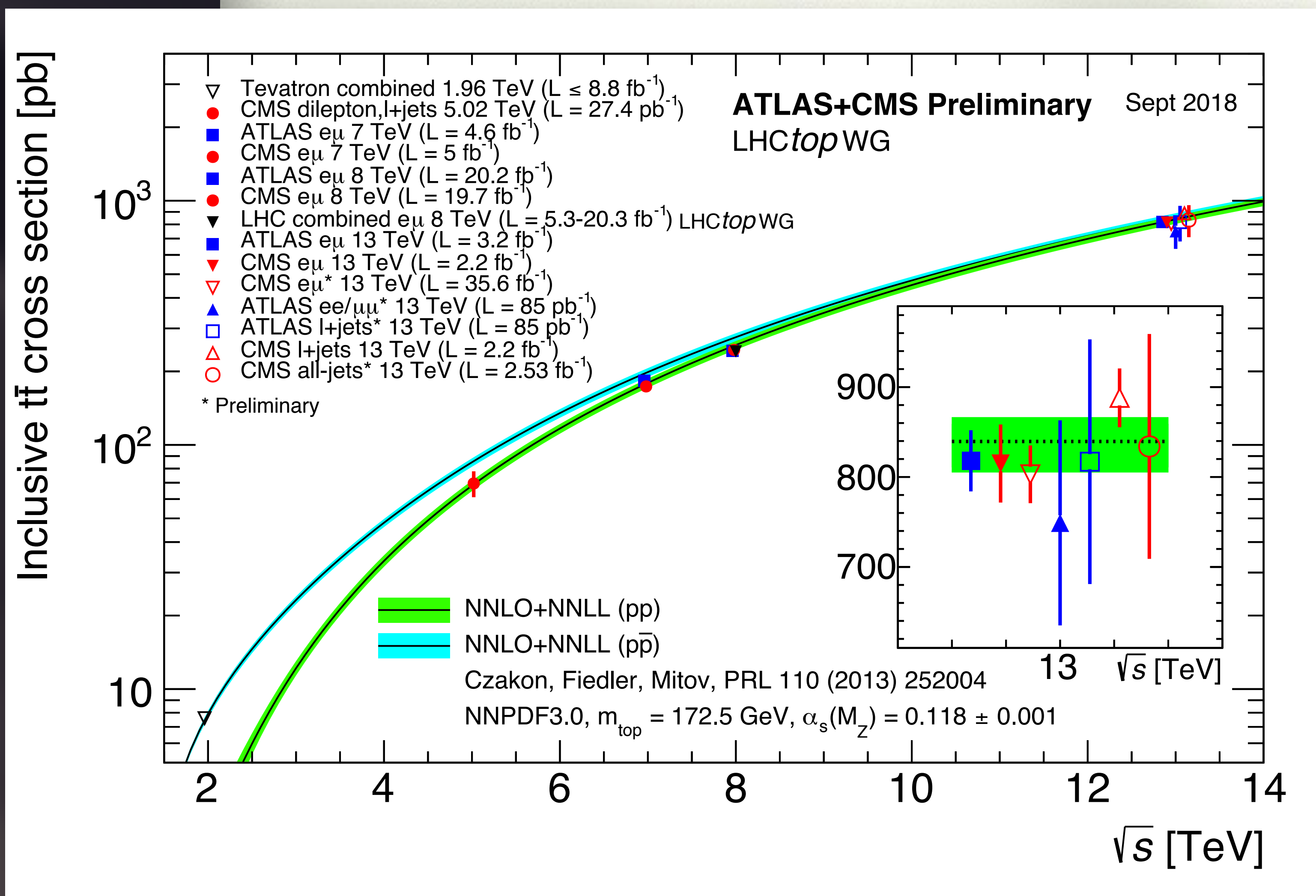






>120 M top quark pairs have been produced in LHC Run-2!

State of Arts: $t\bar{t}$ Production



- Best single channel measurements at 13 TeV:

Ref. PLB 761 (2016) 136

ATLAS eμ w/ 3.2 fb^{-1}

818 ±8$_{(stat)}$ ±27$_{(syst)}$ ±19$_{(lumi)}$ pb

Ref. CMS-PAS TOP-17-001

CMS eμ w/ 36 fb^{-1}

803 ±2$_{(stat)}$ ±25$_{(syst)}$ ±20$_{(lumi)}$ pb

NNLO+NNLL calculation: (m_{top} = 172.5 GeV)

832 ±29$_{(scale)}$ ±35$_{(PDF)}$ ±23$_{(mass)}$ pb

Experimental precision (*totally systematic dominant!*) reached ~4%; theory precision is around 6%.

Must go differential!

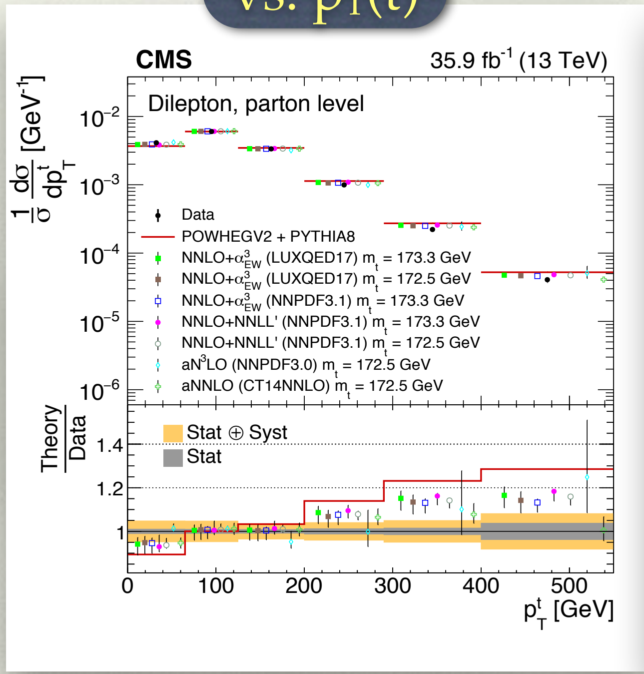
$t\bar{t}$ Differential Cross Sections

Better modeling of MC is truly essential!

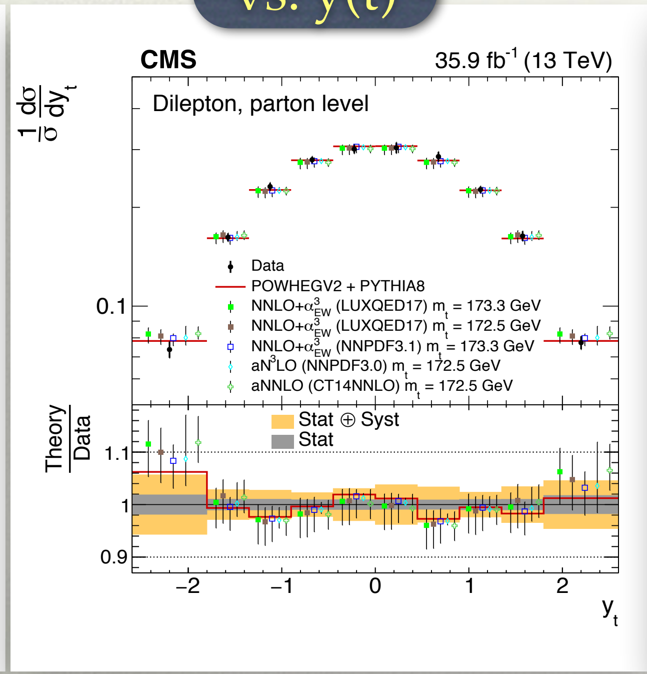
CMS differential cross sections with dilepton $t\bar{t}$

Ref. arXiv:1811.06625, submitted to JHEP

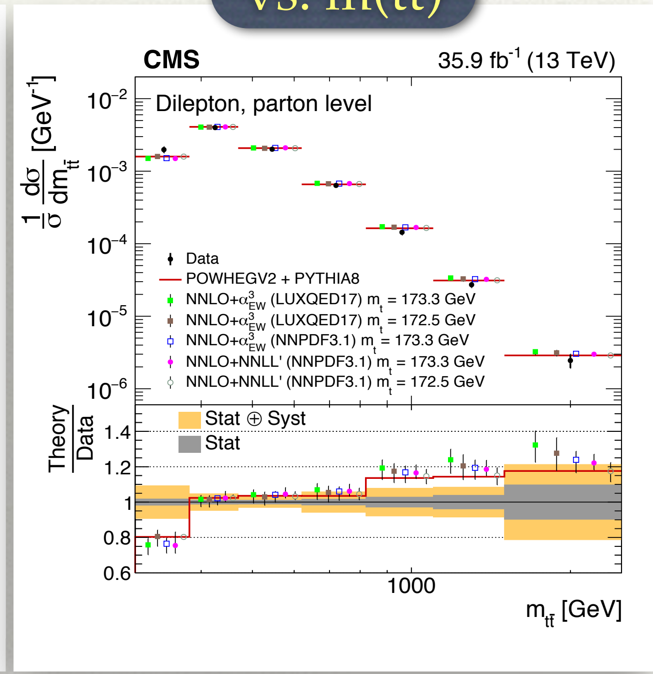
vs. $p_T(t)$



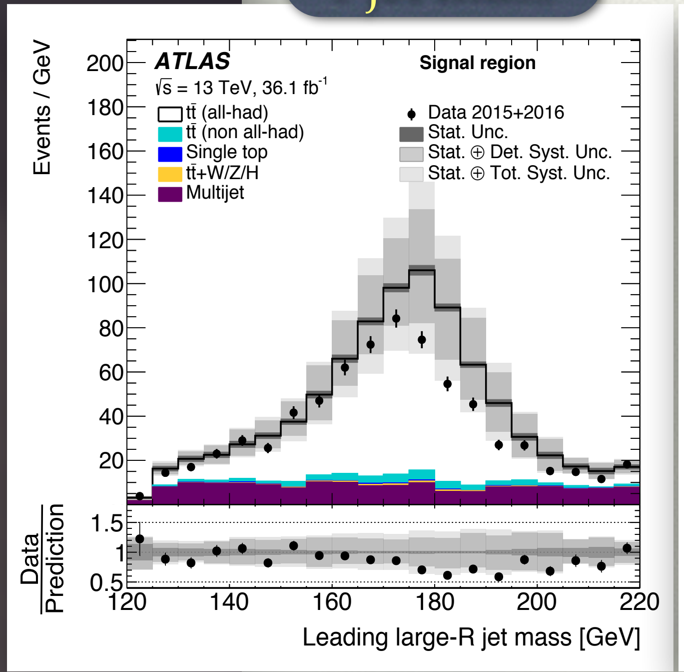
vs. $y(t)$



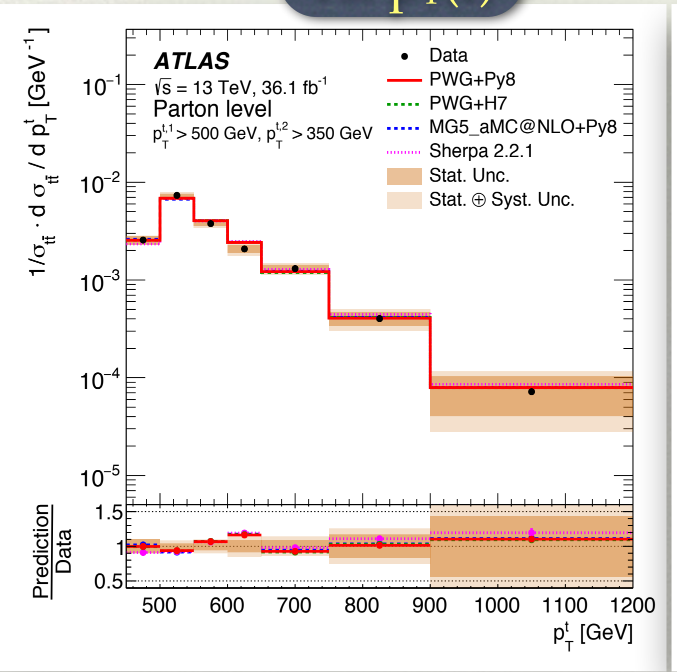
vs. $m(t\bar{t})$



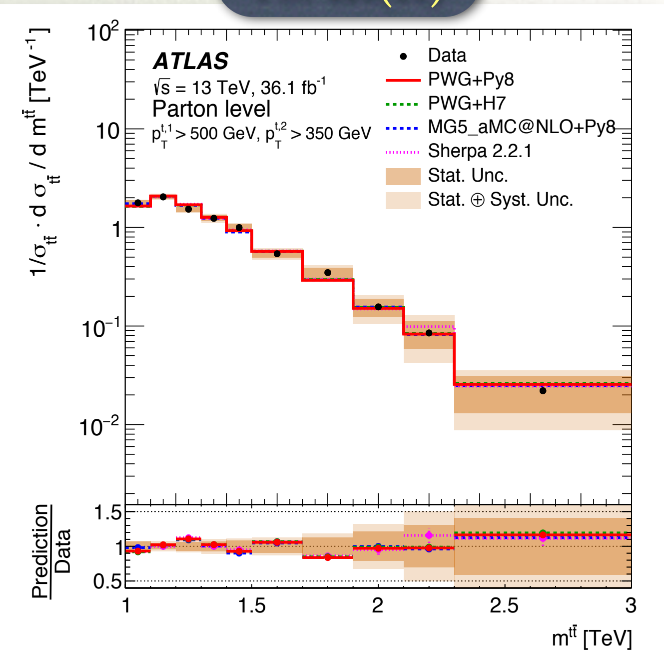
t-jet mass



vs. $p_T(t)$



vs. $m(t\bar{t})$



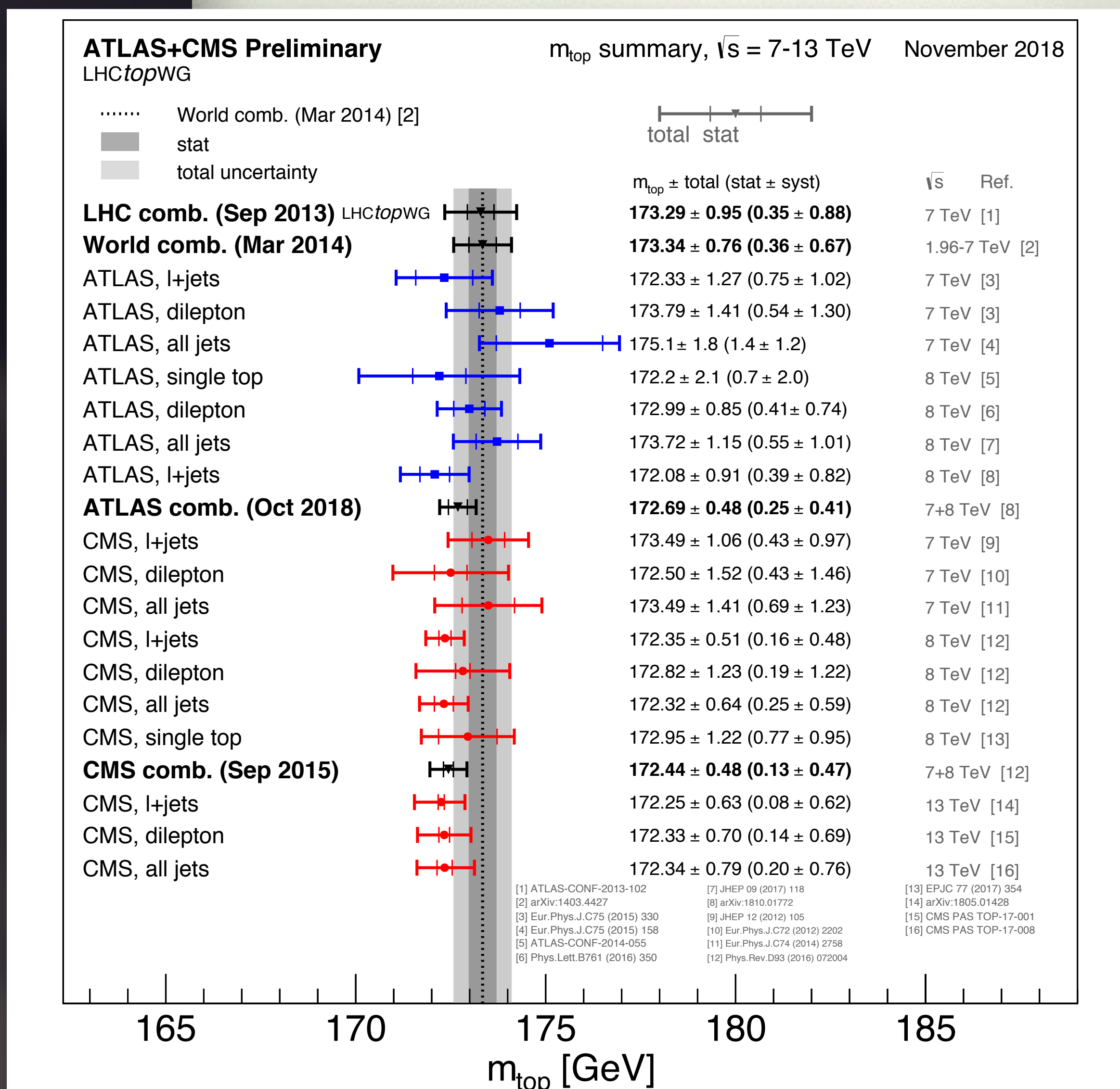
ATLAS differential measurements with boosted hadronic top

high p_T hadronic top quarks! (>500, 350 GeV)

Ref. PRD 98 (2018) 012003

State of Arts: Top Mass

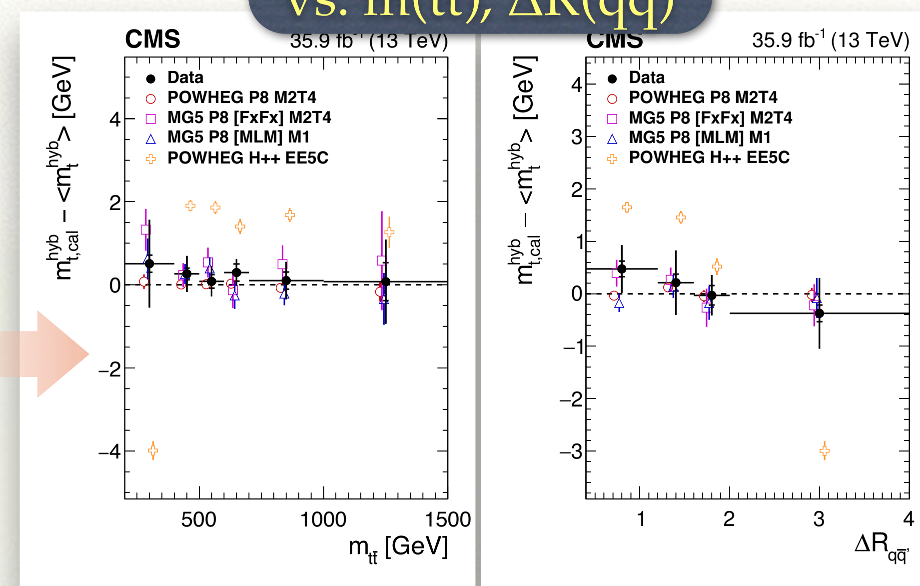
"Classical methods" are all systematic dominant already!



Alternative methods (*e.g. with kinematical endpoint, b-hadron lifetime, etc*) are not yet very accurate, but can have some potential improvement with the upcoming statistics.

vs. $m(t\bar{t})$, $\Delta R(q\bar{q})$

can go differential as well!



Ref. EPJC 78 (2018) 891

ATLAS 7+8 TeV combine
172.69 ± 0.25 ± 0.41 GeV

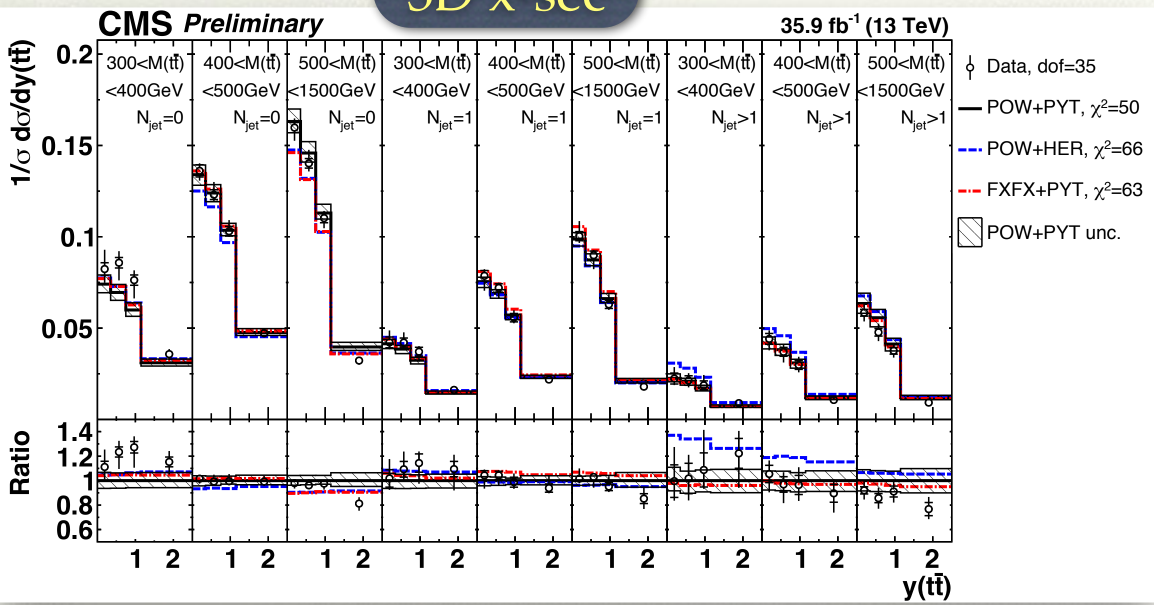
Ref. arXiv:1810.01772, submitted to EPJC

CMS 7+8 TeV combine
172.44 ± 0.13 ± 0.47 GeV

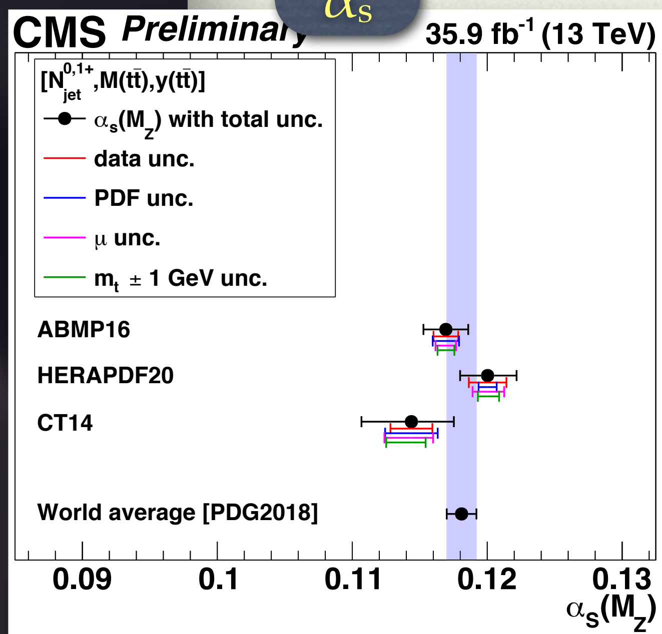
Ref. PRD 93 (2016) 072004

α_s, m_t^{pole} & PDF

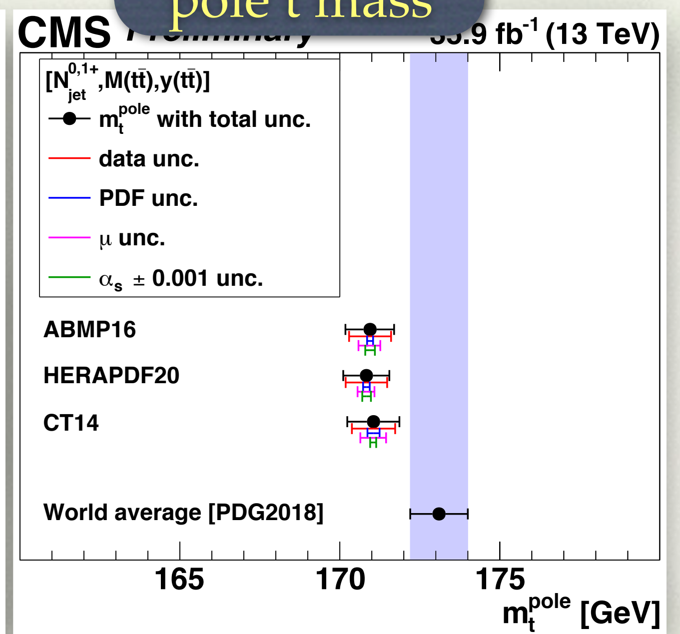
3D x-sec



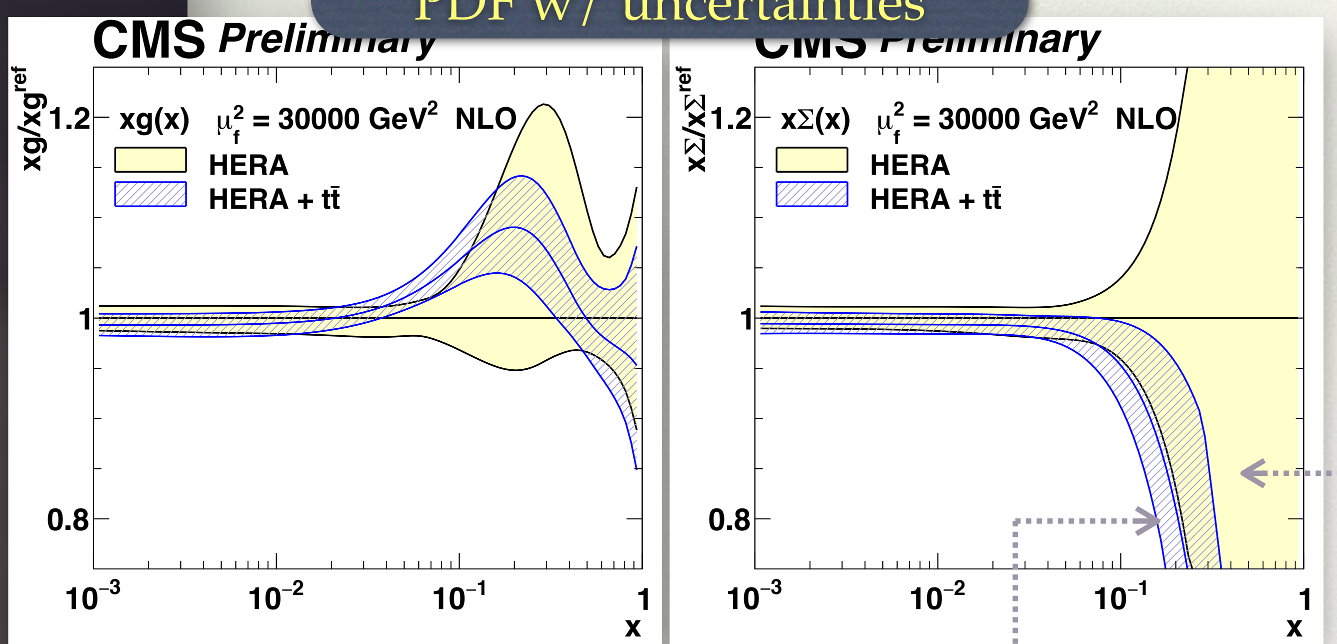
α_s



pole t mass



PDF w/ uncertainties



HERA only

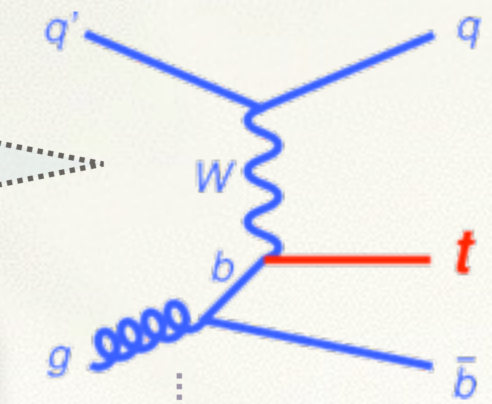
HERA + CMS $t\bar{t}$

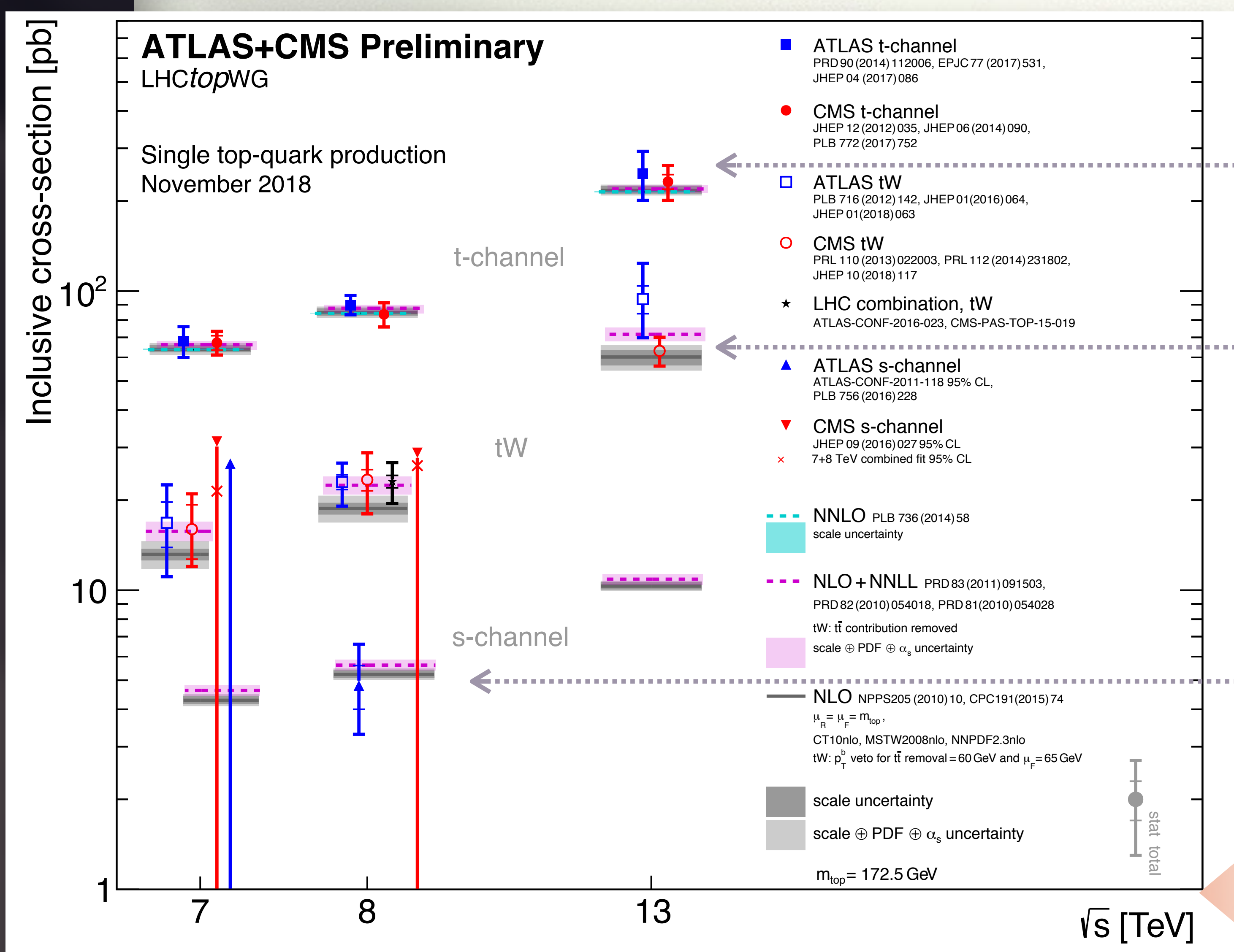
- New result from CMS: based on triple-differential measurements of $t\bar{t}$ cross section in **m($t\bar{t}$)**, **y($t\bar{t}$)**, and # **of additional jets** at 13 TeV:
  - Extract the strong coupling strength α_s and top pole mass with external PDFs.
  - Or a simultaneous fit to PDFs, α_s, and pole m_t — the $t\bar{t}$ data have a significant impact on the gluon PDF at large x!

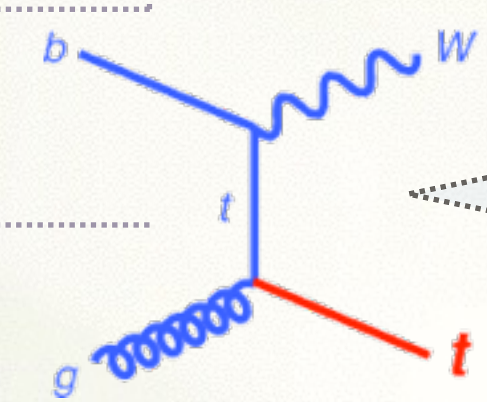
Ref. CMS-PAS-TOP-18-004

Single Top Production

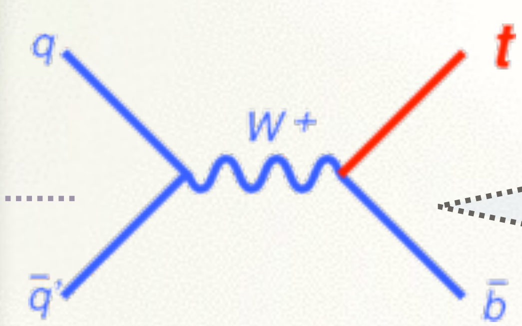
t-channel: already enter precision regime, can be used to derive other parameters, including Vtb.







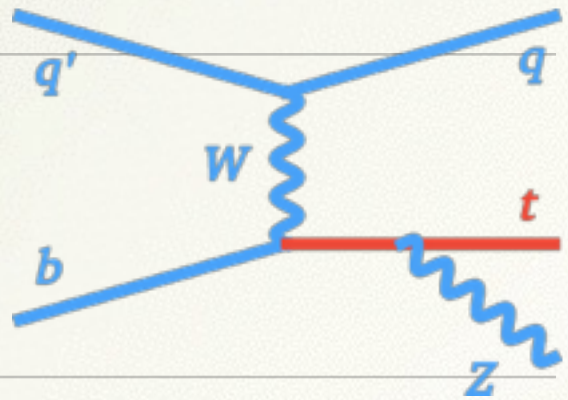
tW-channel: large $t\bar{t}$ background but finally measured.



s-channel: very challenge process, not yet fully measured.

There are smaller processes (σ<1pb!) can be still measured in fact!

Observation of tZq



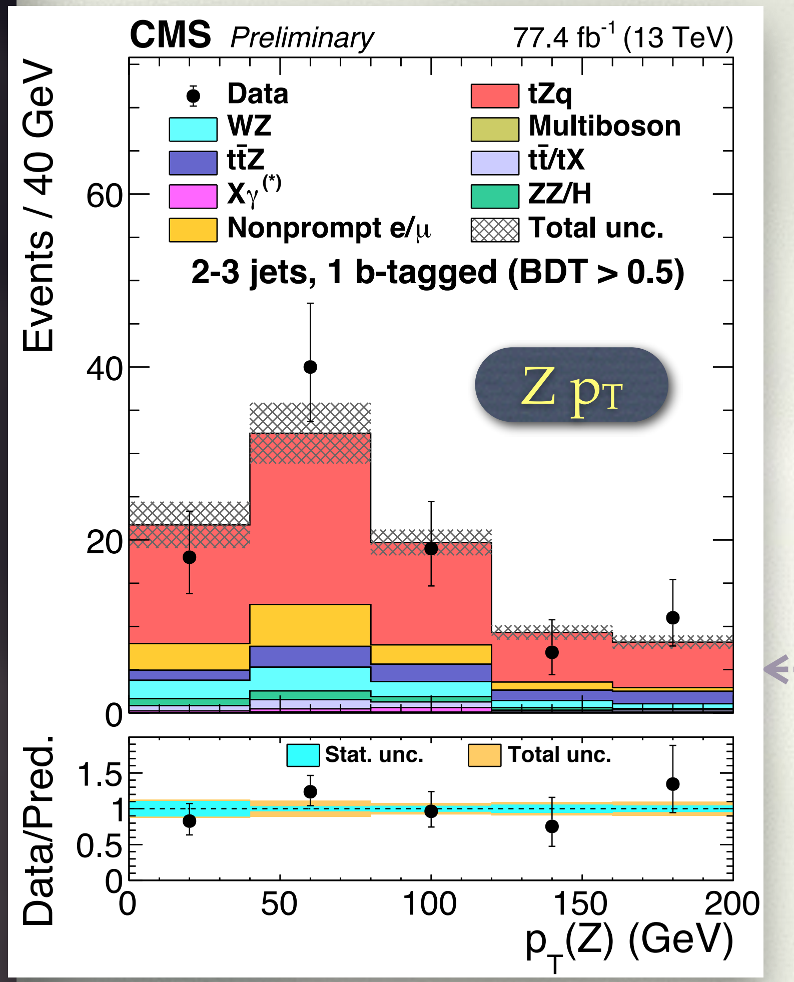
- Single top quark in association with a Z boson is observed with CMS 2016+2017 77 fb^{-1} data.
- Based on a very clean **trilepton+b-jet events** + BDT analysis for background discrimination with $|M(\ell^+\ell^-) - M_Z| < 15$ GeV.

Ref. CMS-PAS-TOP-18-008

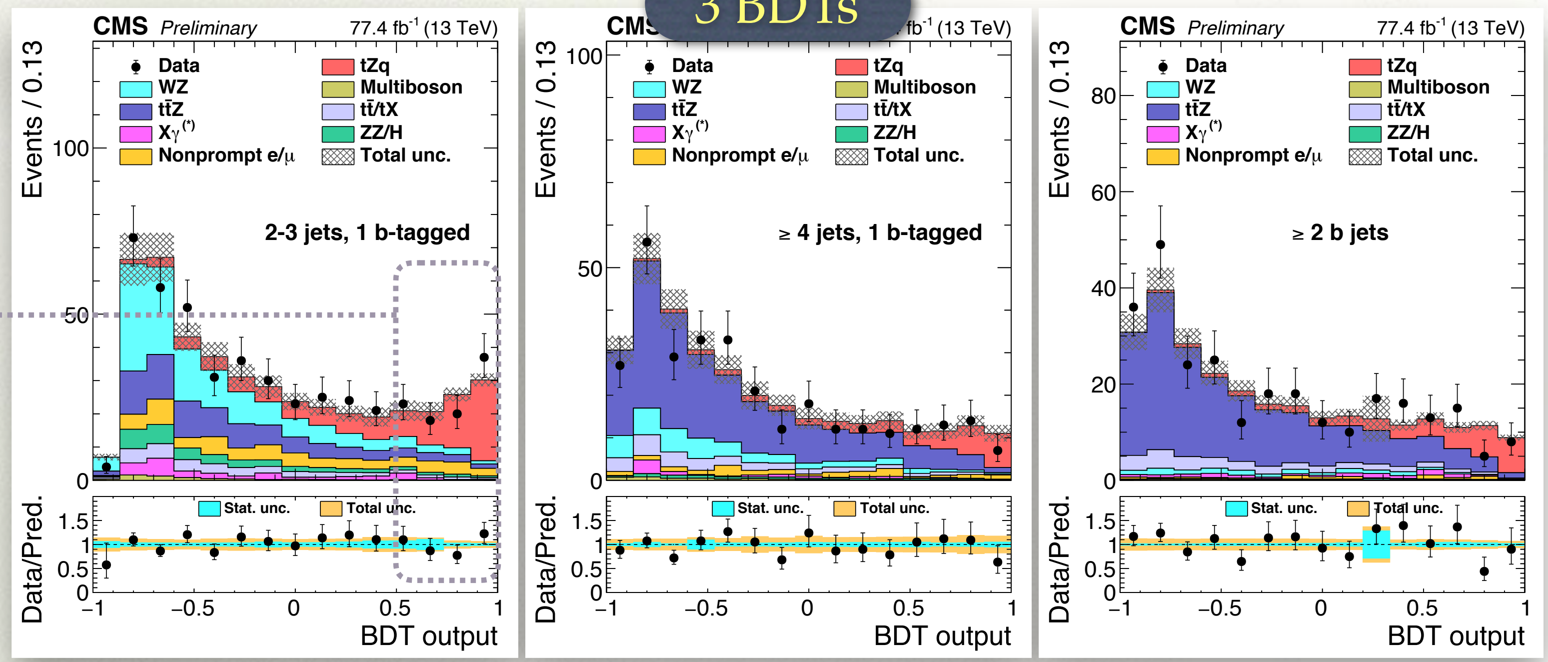
$\sigma(pp \to tZq \to t\ell^+\ell^- q) =$
$111 \pm 13_{(stat)}\,{}^{+11}_{-9}\,(syst)$ fb
obs. (exp.) significance: 8.2σ (7.7σ)

agree with NLO calculation:

94.2 ±3.1 fb

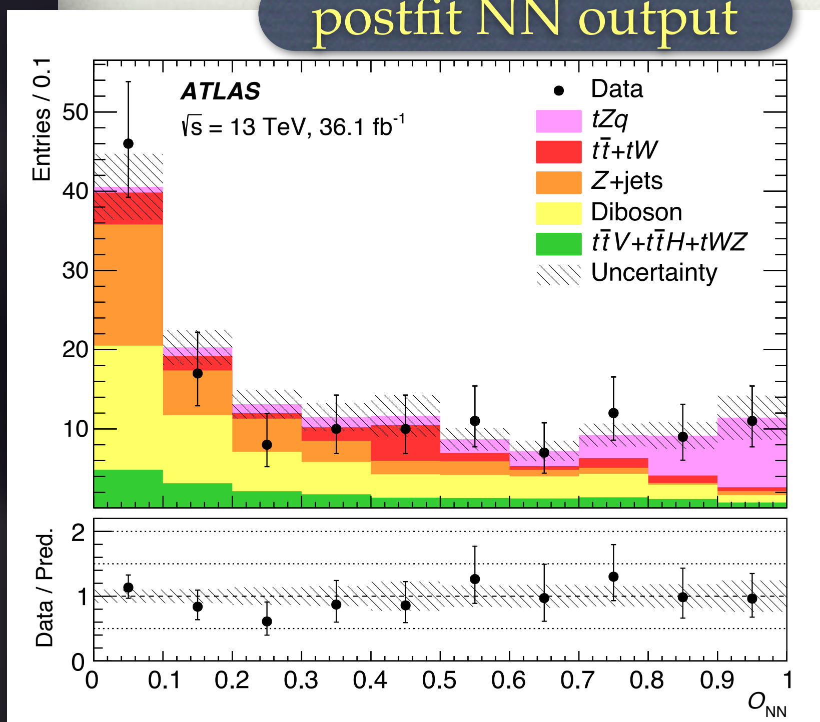


3 BDTs



tZq Production and Others

postfit NN output



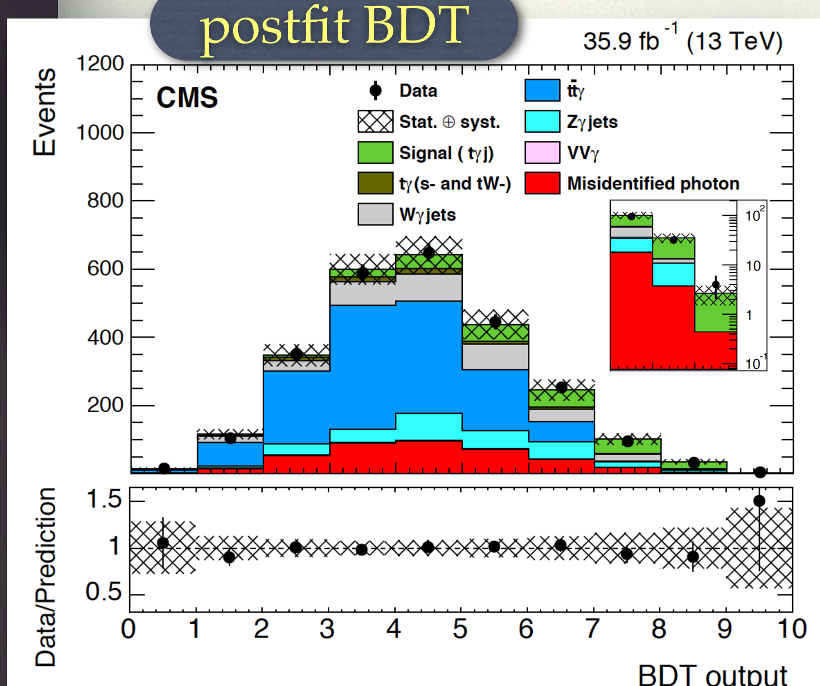
- **ATLAS search of tZq** with 2016 data.
- Look for 3-leptons + 2 jets (1-b-tagged); final discriminant with NN.

Just a little bit shy from 5σ!

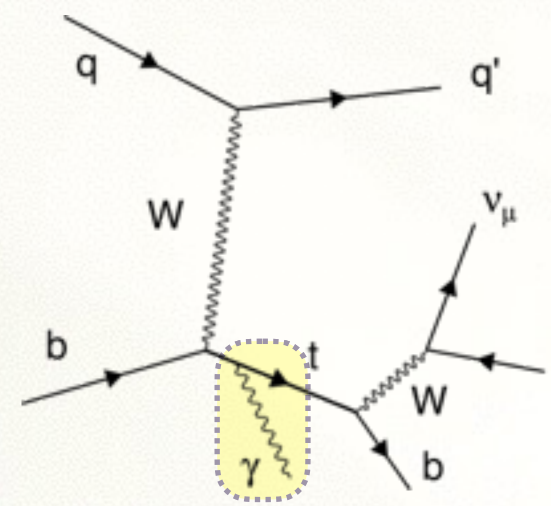
σ = 600 ±170 ±140 fb
obs. (exp.) significance: 4.2σ (5.4σ)

Ref. PLB 780 (2018) 557

postfit BDT



- **CMS search of single t+γ** with 2016 data.
- Look for μ+γ+2 jets (1-b-tagged); final discriminant with BDT.



Evidence as well!

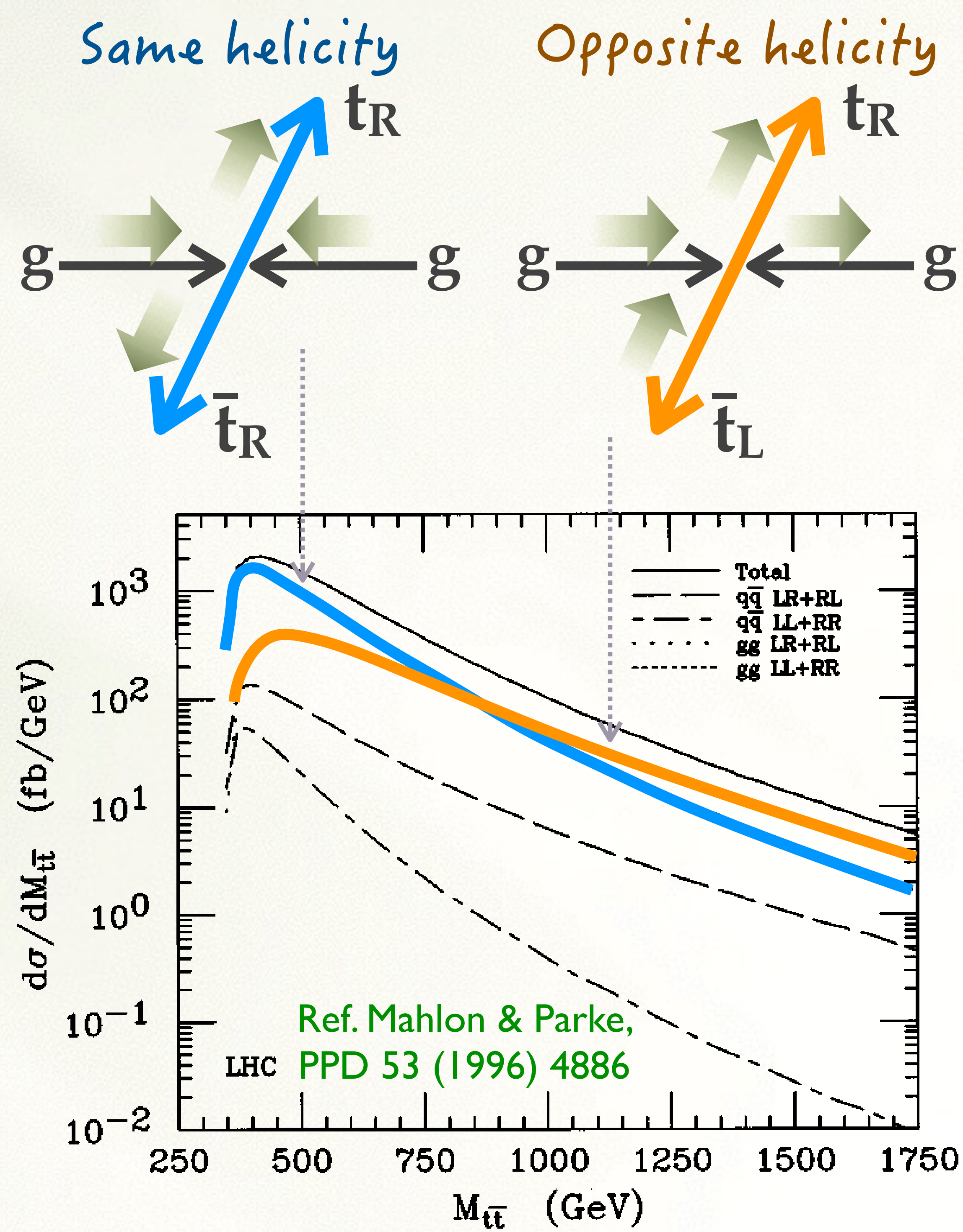
σ = 115 ±17 ±30 fb
obs. significance: 4.4σ

Ref. PRL 121, 221802 (2018)

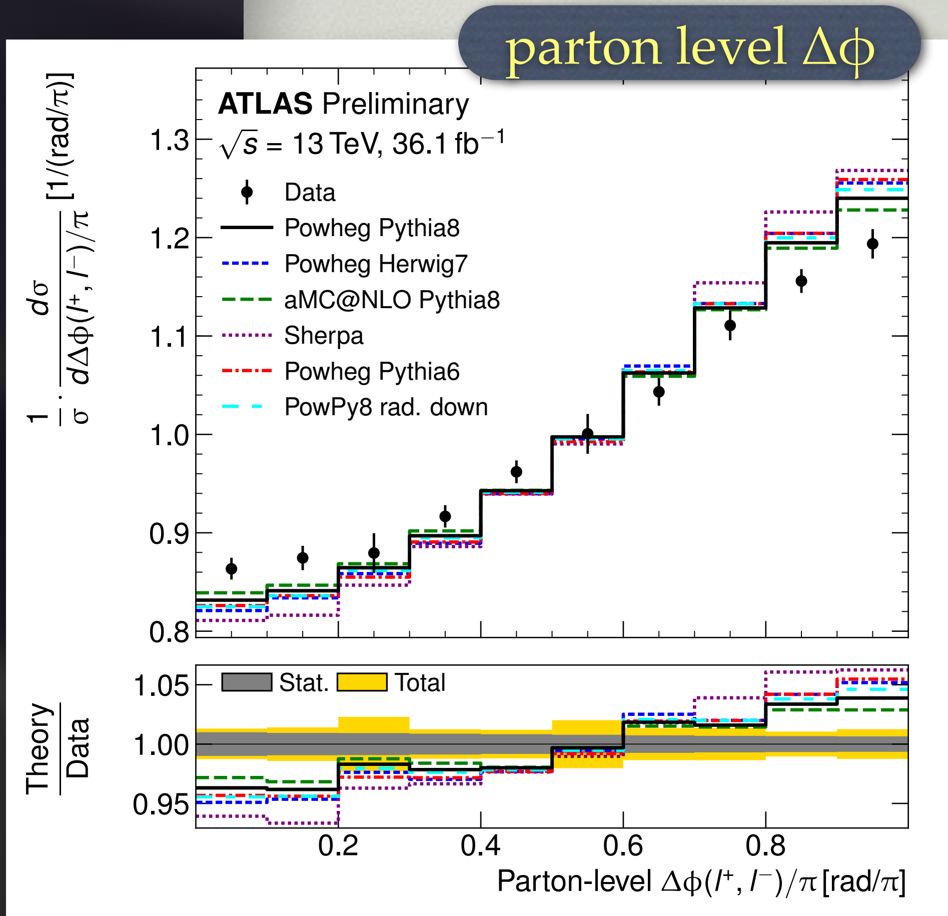
Top Spin Correlations

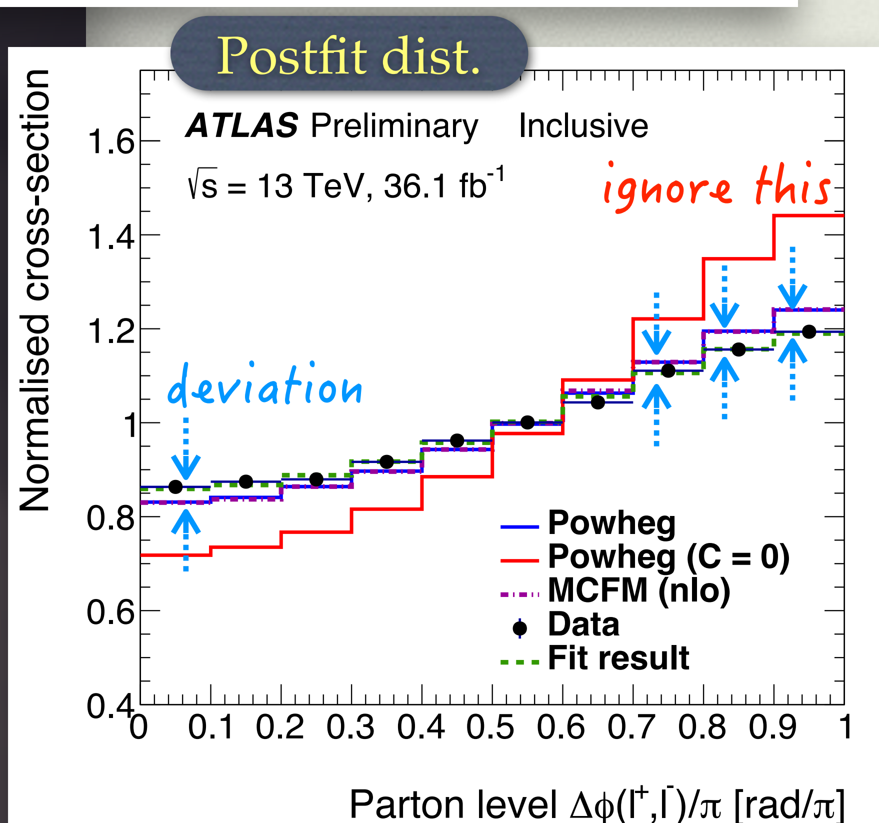
- Spins of top pairs are **strongly correlated** at the production:
  - **Low M($t\bar{t}$): RR/LL dominate**
  - **High M($t\bar{t}$): RL/LR dominate**
- Top quark decays before hadronization; spin information transferred to daughter particles.
- SM-extended models can modify spin polarization and correlation of top quarks though *new mediator* or *new heavy particle decay to top*.

➡ **An excellent probe of NP!**



Excess of Deviation!?





- **ATLAS spin correlation analysis** with top decay pair decays from 13 TeV 2016 data:
  - Very clean dileptonic $t\bar{t}$ sample ($e\mu$) used.
  - Check the **Δϕ between the two leptons**; no needs of kinematic reconstruction.
  - Extract the fraction of SM-like spin correlation ($\mathbf{f_{SM}}$) from fits to the unfold parton level data.

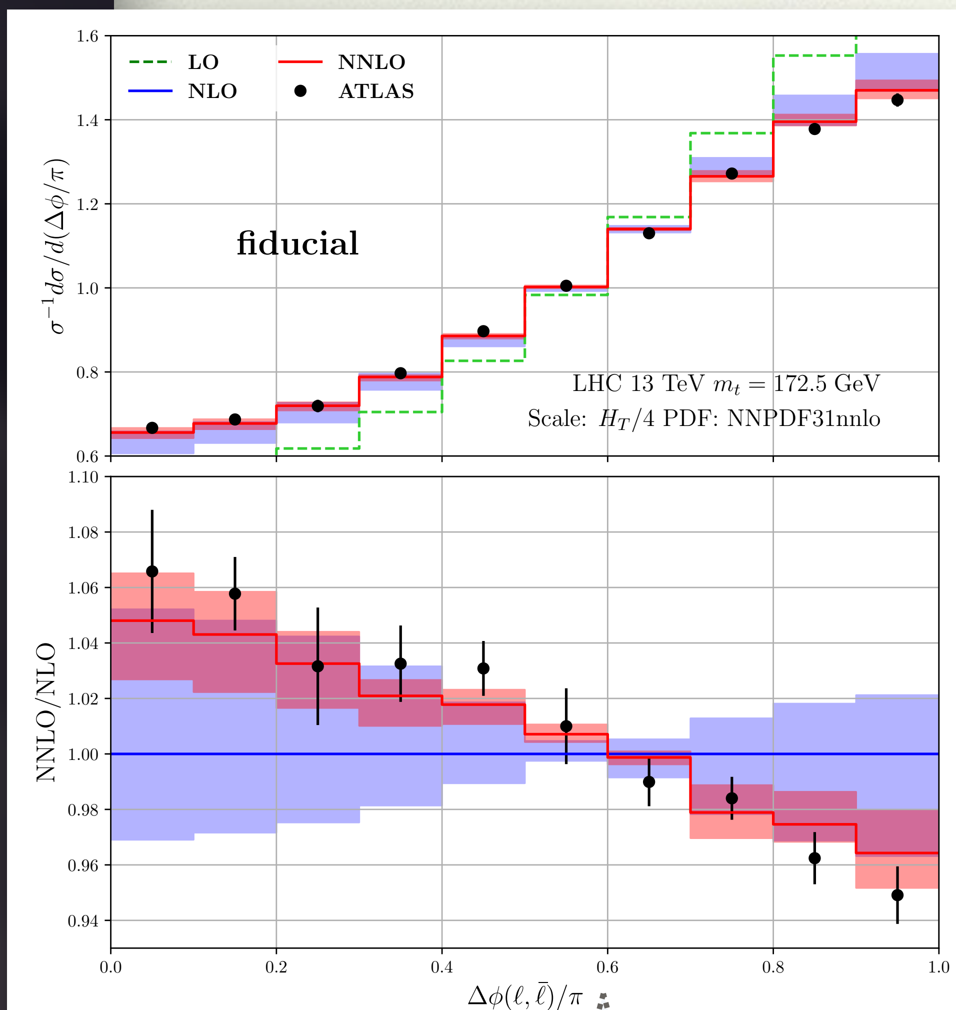
Ref.ATLAS-CONF-2018-027

M($t\bar{t}$) region	f_{SM}	Sig. (inc. TH unc.)
<450 GeV	1.11±0.04±0.13	0.85σ (0.84σ)
450-550 GeV	1.17±0.09±0.14	1.00σ (0.91σ)
550-800 GeV	1.60±0.24±0.35	1.43σ (1.37σ)
>800 GeV	2.2±1.8±2.3	0.41σ (0.40σ)
Inclusive	**1.250±0.026±0.063**	**3.70σ (3.20σ)**

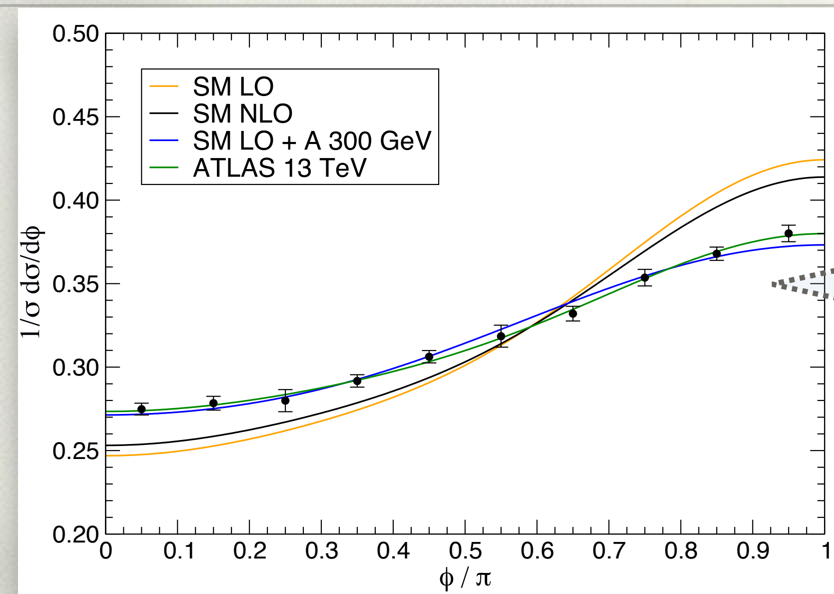
3.2σ deviation w.r.t. the NLO prediction

Adding more “N” might help?

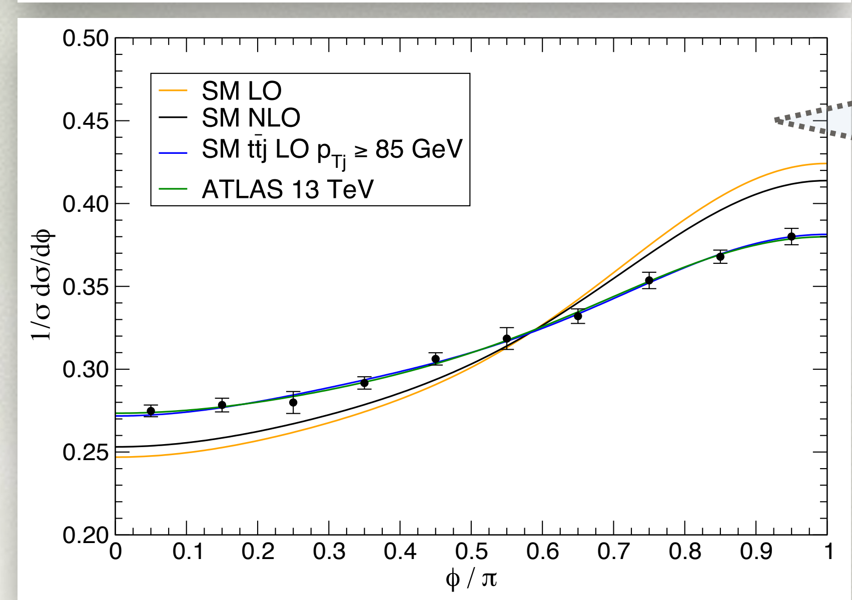
Ref. Talk by Rene Poncelet



It seems that the recent **NNLO** calculations improve the description



Or adding a 300 GeV pseudoscalar mediator



Or simply require different kinematics in the tt+jet

Ref.
Talk by J.A. Aguilar-Saavedra
JHEP 09 (2018) 116

A general comment is $\Delta\eta$ also useful!

https://indico.cern.ch/event/746611/

See the contributions at recent LHC TOP WG Meeting!

CMS Results

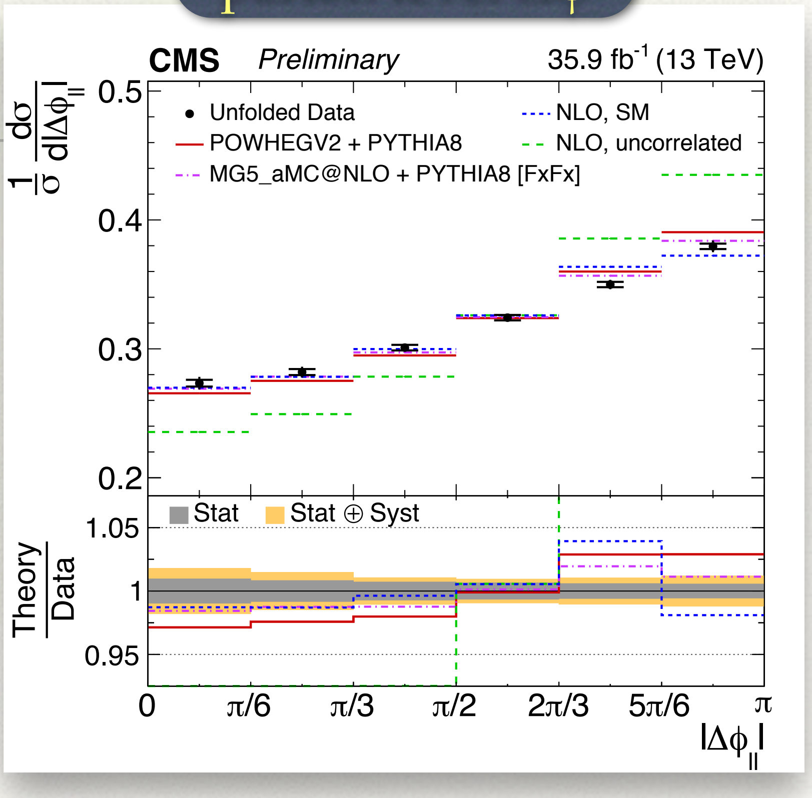
Ref. CMS-PAS-TOP-18-006

- CMS measures op quark polarization and spin correlations using 2016 13 TeV data.
- Parton-level differential cross sections which are sensitive to the spin-dependent parts tt production density matrix are measured.

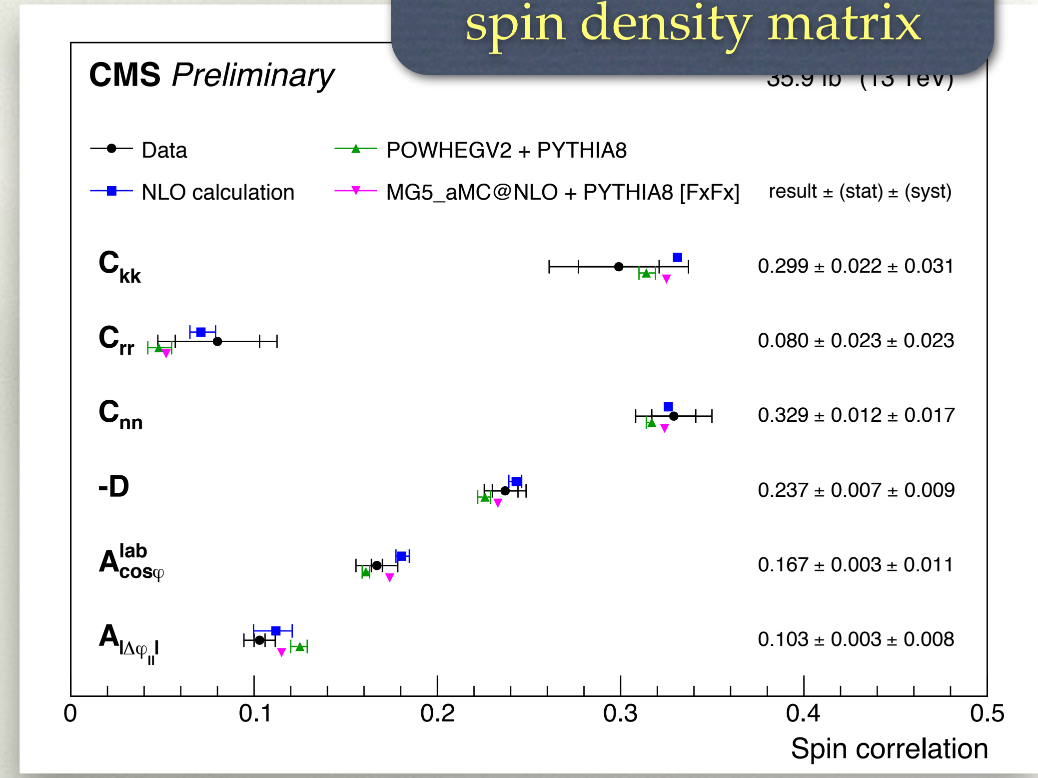
Constraint to Chromomagnetic Dipole Moment also provided.

No significant deviations, seem to agree with the NLO predictions.

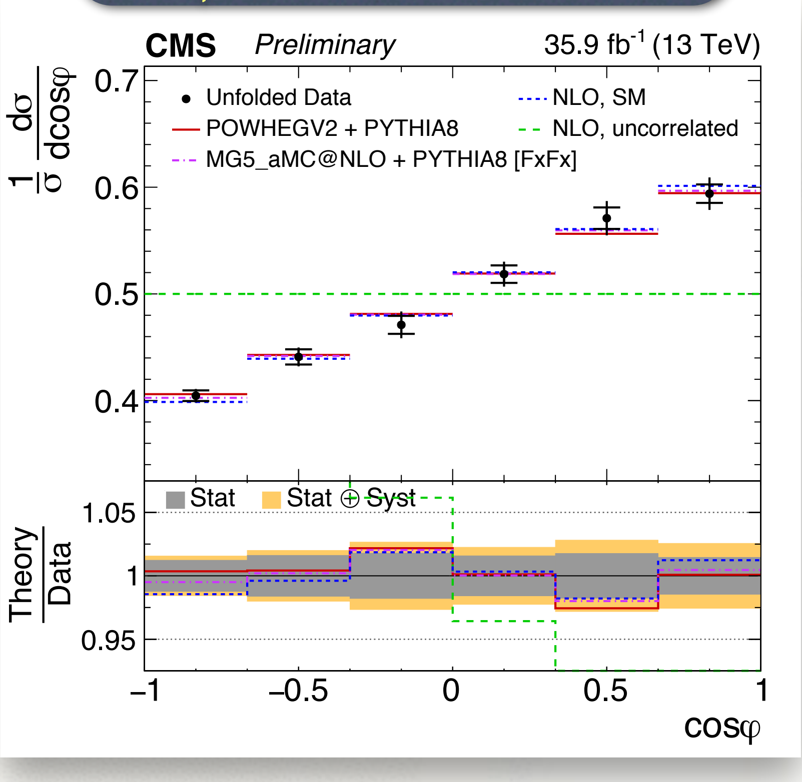
parton level $\Delta\phi$



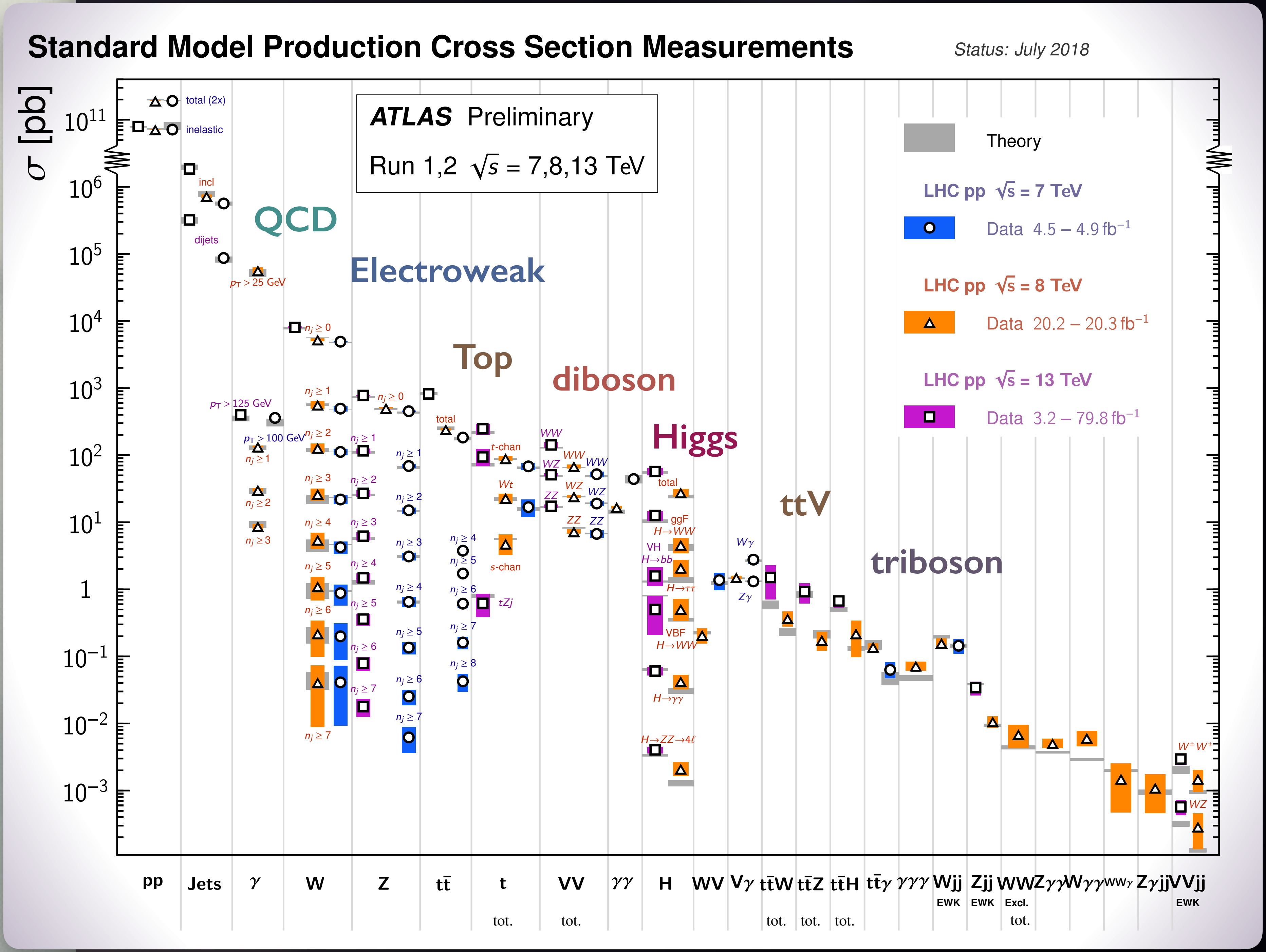
Diagonal elements in the spin density matrix



$\cos\phi$ of $\ell^+\ell^-$ at rest frame



Wrap up: the Standard Model

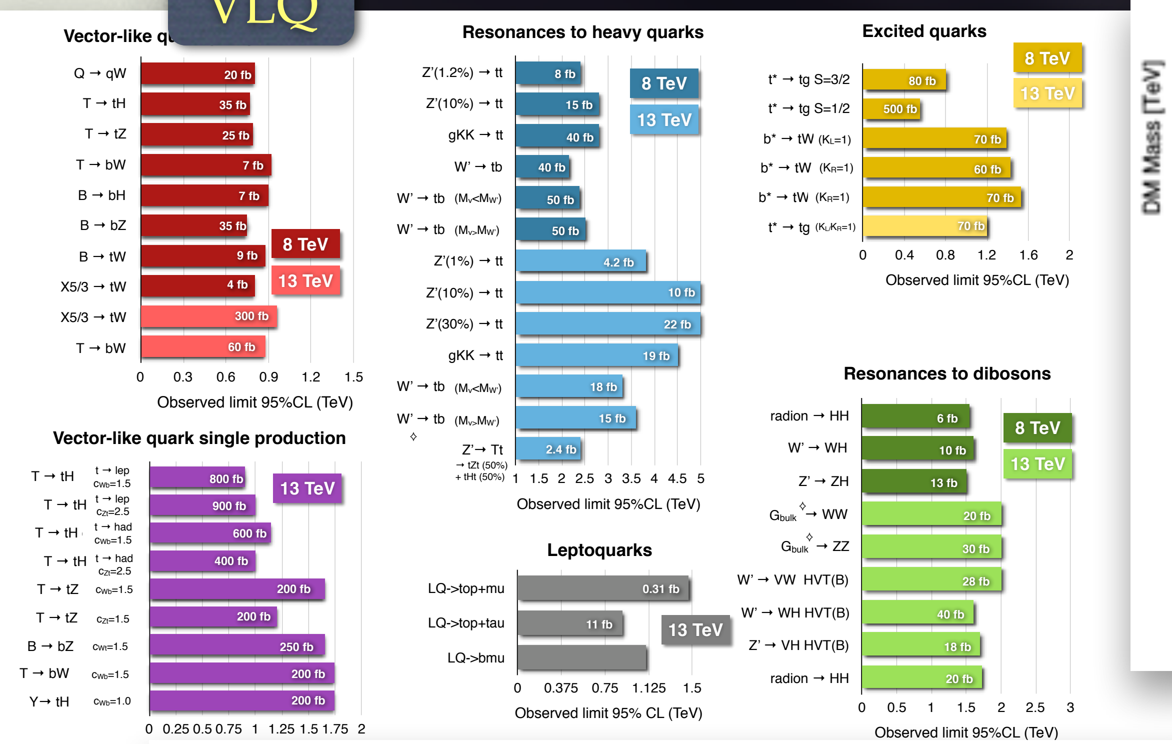


Excellent agreement throughout 9 orders of magnitudes; SM is getting stronger still.

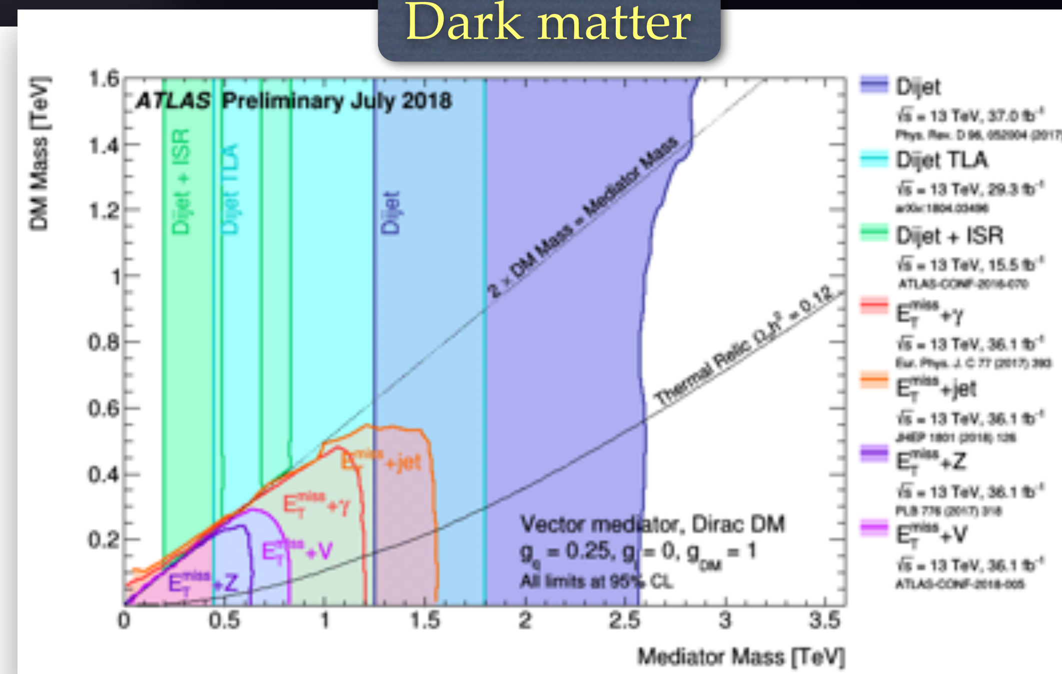
Start to measure the SM process below 1 pb

Wrap up: Beyond the SM…

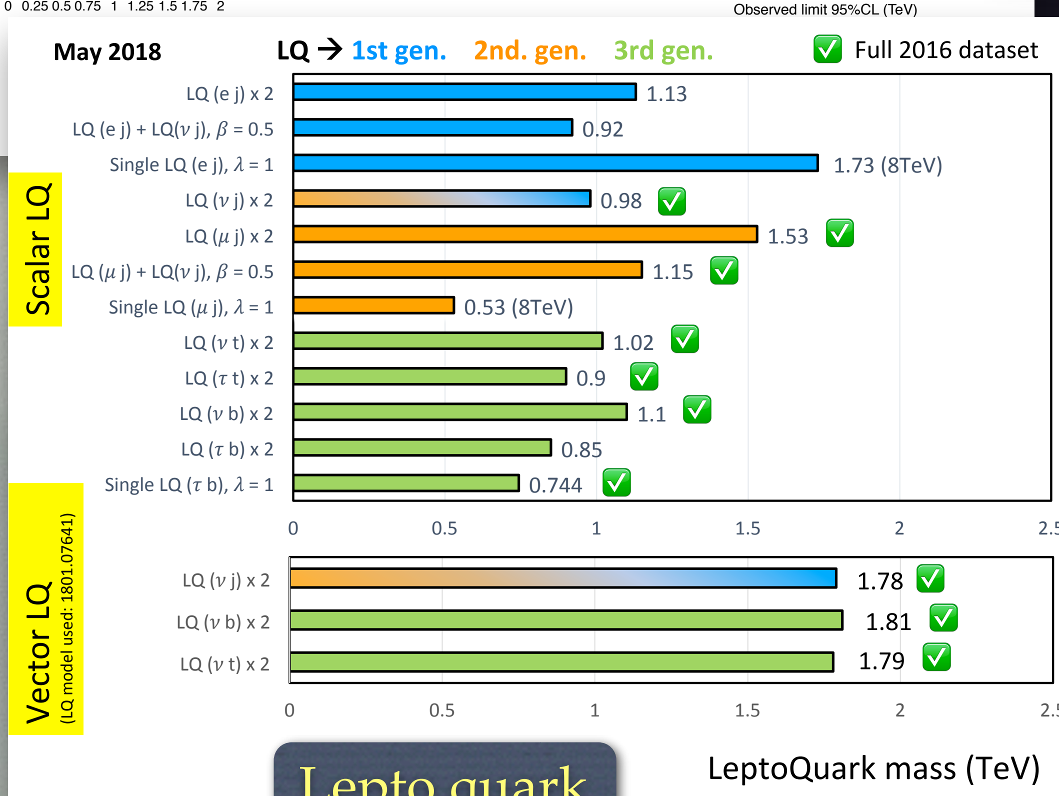
VLQ



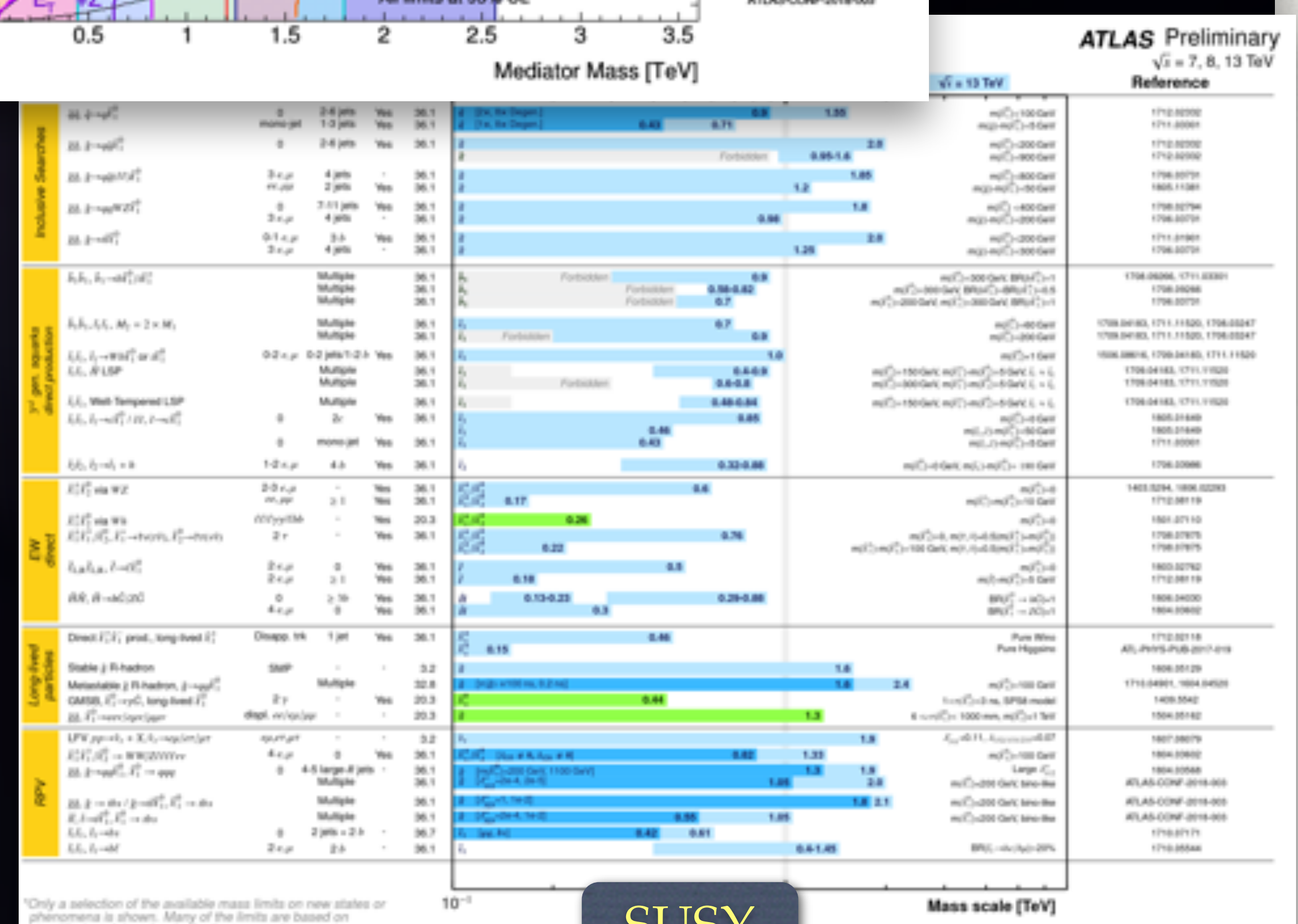
Dark matter



SIMPLY STRONGER LIMITS…

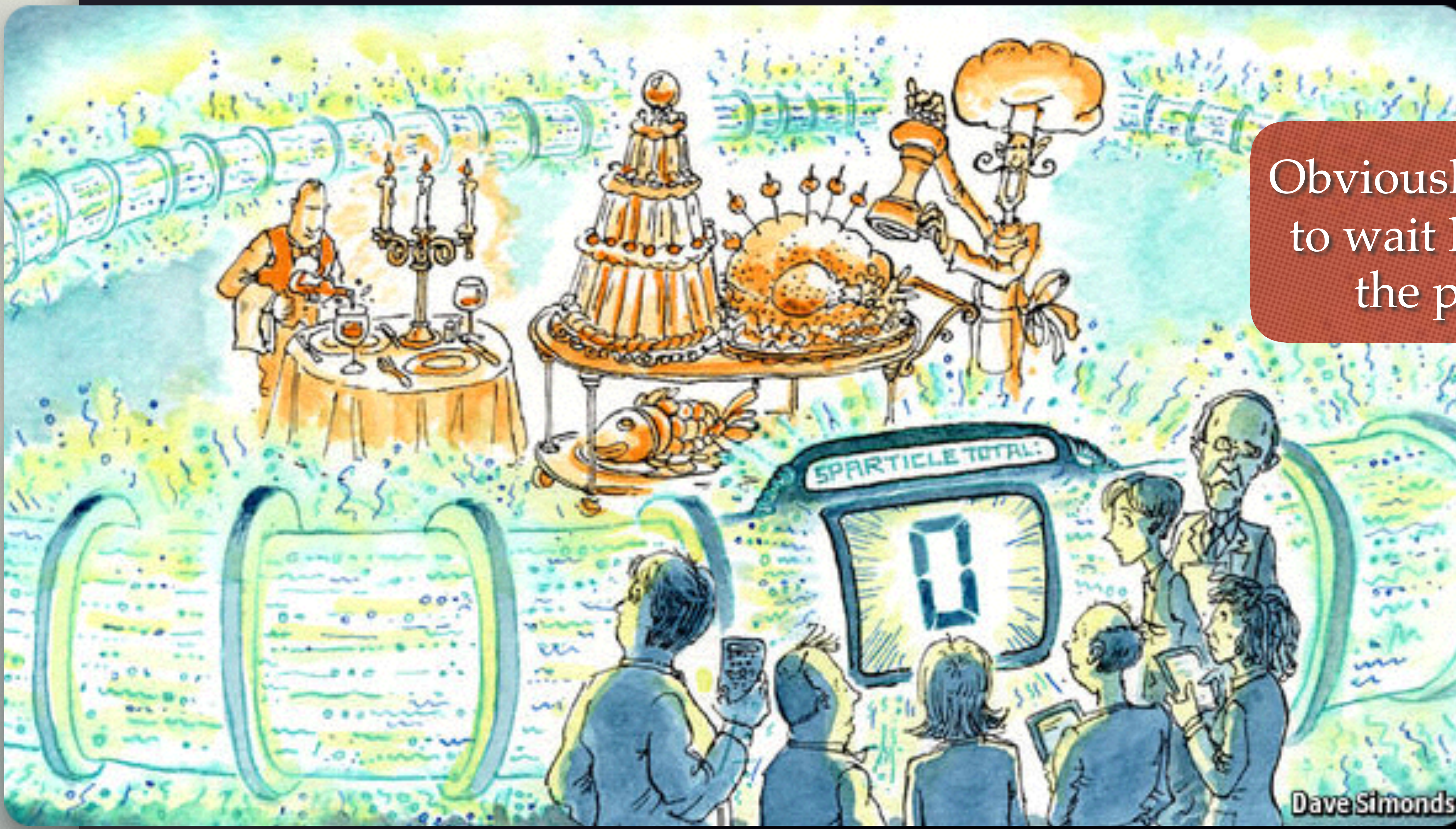


Lepto quark



SUSY

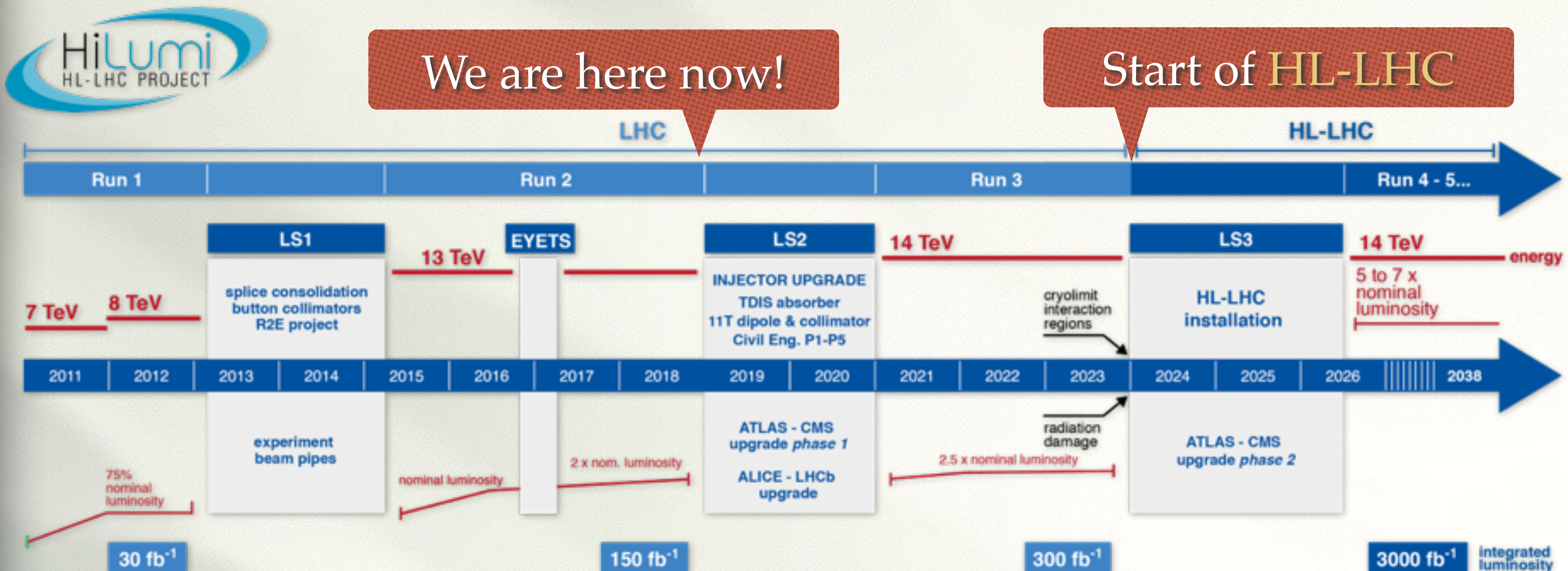
Wrap up: Beyond the SM…(cont.)



Obviously we need to wait longer for the party…

LHC Outlook & Plan

Not too much time to prepare!



- **HL-LHC is just ahead of us, expected to collect 3000 fb^{-1} of data**; maximize the reach for the searches and for precision measurements.
- All experiments plan to upgrade the detectors during either 2019-2020 or 2024-2026 for HL-LHC environment (*tolerance with a much higher pile-up, aiming for a higher precision, etc*).
  - ➡ LHC will operate till ~2037; only ~5% of the collisions delivered so far!

Summary

- **LHC continue to explore the Terascale regime!**
- **On the Higgs boson:** this year the ttH production and $B \rightarrow b\bar{b}$ decay are finally observed with new 13 TeV data. The boson is very consistent with Standard Model expectations, still.
- **On the Top quark:** high quality measurements are carried out by the LHC experiments. Precise measurements require precise calculations for a better understanding/modeling of the data.
- Measurements of SM processes show good agreement with predictions. No sign of new physics so far and the left space of SM-extended models is squeezed.

Backup Slides